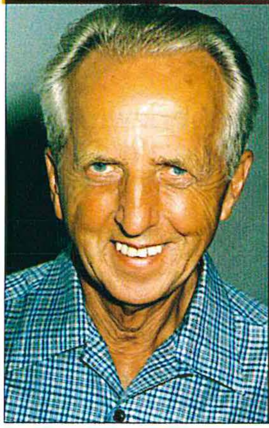

Actual and Predicted Shot Peening Indentations

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

Shot peening involves the covering of components with indentations. Those indentations induce a surface layer of compressive residual stress that enhances component properties. Two parameters are of primary importance – they are the **size** of individual indentations (which governs the depth of the compressed surface layer) and the **coverage** by indentations (which is proportional to the indent size multiplied by both the rate of indent formation and the time of peening). Both of these primary parameters are proportional to the average size of the peening indentations. We should, therefore, know what factors affect the size of the indents that we are inducing.

The previous paper in this series presented a hypothetical model showing how the diameter of a shot peening indent could be predicted using a knowledge of the major peening variables. That model was based on the premise that the volume of an indent, V, is simply the work done by the indenting shot particle, W, divided by the work needed to produce each unit volume of indent, B. Hence, V = W/B. It was shown that the most important factor controlling indent diameter was shot diameter, with a smaller effect being given by shot velocity and even smaller effects by material strength and shot density. In order to carry out quantitative studies of the relationships between these variables we need a controlled 'laboratory' method of producing indents. The most obvious, well-established, method is to drop balls from known heights so that we can have accurate estimates of the ball velocity. The disadvantage of that technique is that very low impact velocities are induced so that large balls have to be used in order to produce measurable indents. The indents are very shallow so that edge definition is poor, making them difficult to locate. An alternative presented here is to use 'weighted balls', where small diameter balls are backed up by relatively-large masses of material. With a large mass the kinetic energy, $1/2mv^2$, then becomes large enough to produce sharply-defined indentations.

The aims of this paper are to (1) show how controlled indentations can be produced out using simple experimental procedures and (2) to compare actual indent diameters with those predicted using the hypothetical model. Only if supporting experimental evidence is available can a hypothesis be converted into a theory.

EXPERIMENTAL PROCEDURES

The simplest relevant experimental procedure involves dropping spheres from known heights onto thick strips of component material. Indent diameters, d, can be measured using a measuring eyepiece attached to a standard bench microscope. Sphere diameters can be measured using either a vernier micrometer or the measuring eyepiece. The proportion of energy transferred from the moving sphere to the component material, P, is simply $(1 - h_2/h_1)$. The rebound height can be estimated visually but more accurate values can be obtained using a video camera. Fig.1 shows, schematically, an experimental set-up for which a vertical scale, e.g. a metre rule, has been included. The anvil should be massive relative to the ball diameter and specimen thickness. Ball bearings are appropriate for experimental purposes as they are manufactured to high tolerances in terms of sphericity and reproducibility.

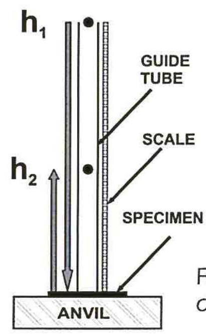

Fig.1 Ball-dropping equipment with ball dropped from h_1 and rebounding to h_2.

A ball dropped from a height, h_1, accelerates due to gravity, g, reaching a velocity, v, when it impacts the specimen. That velocity can be estimated using basic physical principles. As an example, using whole numbers, consider raising a ball having mass of 1kg to height of 1m against a gravitational resistance of $10ms^{-2}$. The work done in raising the ball is 1kg x $10ms^{-2}$ x 1m or $10kgm^2s^{-2}$ (equal to 10Nm). This work is converted into kinetic energy, $1/2mv^2$, when the ball is dropped onto the specimen. m is the mass (1kg) of the ball and v is the impact velocity. Ignoring air resistance, the work done in raising the ball is exactly the same as the kinetic energy on impact, 1/2 x 1kg x v^2. Therefore, $10kgm^2s^{-2} = 1/2kg\ v^2$ giving that $v^2 = 20m^2s^{-2}$ or v = $4{\cdot}5ms^{-1}$. In general:

$$\mathbf{v = \sqrt{(2 \times g \times h_1)}} \qquad (1)$$

where **v** is velocity, **g** is the acceleration due to gravity and $\mathbf{h_1}$ is the drop height.

In order to increase the velocity by a factor of 10 (to $45ms^{-1}$ as a realistic practical peening velocity) we would have to drop the ball from a height of more than 100m and even then we would not know the precise velocity. At high velocities, air resistance slows down a falling ball significantly. A 'terminal velocity' can be reached – as experienced by parachutists. Limiting our experiments to a few metres of drop height for large-diameter balls means that air resistance can be ignored. Small-diameter balls have a large surface area/mass ratio so that air resistance cannot be ignored.

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An alternative approach is to use 'weighted balls'. The principle involved is the same as that employed in rebound hardness testers – such as the Shore Scleroscope. A relatively-large mass is attached to a small-diameter indenter and dropped onto the component. Low-load Brinell hardness testers employ a 'captive ball' principle. Fig.2 shows the principle of the mechanism involved.

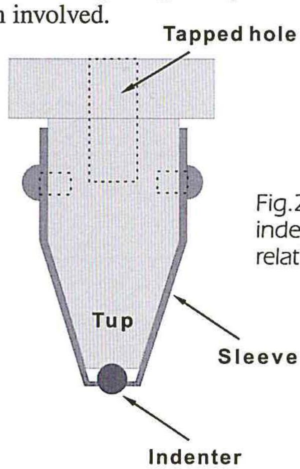

Fig.2 Captive spherical Brinell indenter held against a recess in a relatively-massive tup.

The sleeve shown in Fig.2 is held onto the anvil by two screws and allows for easy replacement of worn indenter balls. Unscrewing the tup from a low-load Brinell tester provides a 'ready-made' weighted ball. The kinetic energy, $1/2mv^2$, of the weighted indenter has to be large enough to create a reasonable size of indentation. A mass 400 times that of the indenter ball is equivalent to a 20 times increase in velocity.

EXPERIMENTS AND RESULTS

Ball-drop experiments

Measurements were carried out involving dropping a series of steel ball bearings from a height of 1.00m, generating a velocity of $4.5ms^{-1}$, onto flat specimens of either mild steel or aluminium. Fig.3 illustrates both linearity of indent diameter/ball diameter and also the effect of specimen thickness. For the 2mm thick aluminium strip the indents created by balls above 15mm diameter are larger than those predicted by a linear relationship. That effect is caused by 'through deformation'.

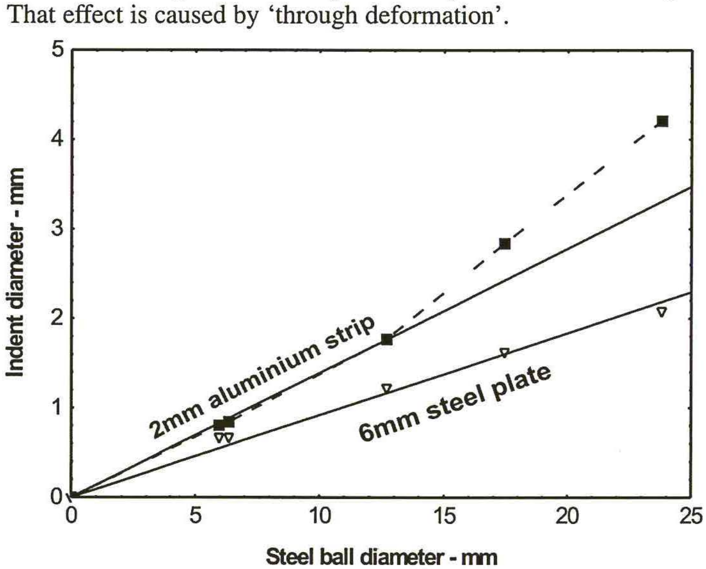

Fig.3 Linear relationships between indent and indenter diameters.

Fig.4 shows measurements made of the indent diameters induced by dropping a 17.46mm diameter steel ball bearing from different heights onto mild steel plate. Ball velocity on impact is proportional to the square root of drop height and indent diameter is proportional to the square root of velocity. It follows that the indent diameter should be proportional to the fourth root of the drop height. The best-fitting fourth root equation shown in fig.4 is a reasonable fit. That confirms that indent diameter is proportional to the square root of velocity – as predicted by the hypothetical model.

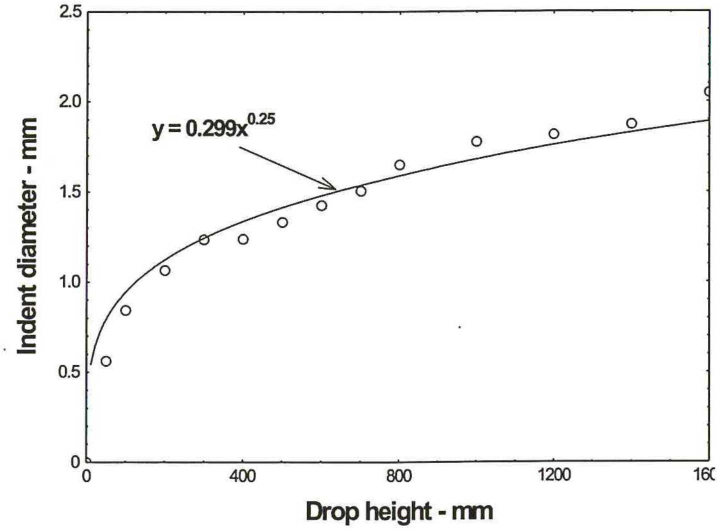

Fig.4 Effect of drop height of steel ball on indent diameter induced in mild steel.

Measurements of the proportion of kinetic energy absorbed on impact, P, were carried out by simply dropping balls of different materials onto plates of different materials and comparing drop and rebound heights. Preliminary experiments had involved dropping steel balls onto a cast iron anvil and had indicated that P was in a range of 0.4 to 0.6. It was now found that much larger values of P occurred when steel, aluminium, copper and brass were used as target materials and ranged from 0.72 to 0.81 when steel balls were dropped. Glass balls dropped onto steel plates gave P values ranging from 0.48 to 0.54.

Brinell Hardness Tests

Brinell hardness tests were carried out, using a variety of applied loads, on a variety of potential test strip materials, see Fig.5. The objective was to ensure that the test strips gave consistent indent diameters for a 2mm Brinell indenter ball. The actual Brinell values were also needed to assess the validity of the theoretical equation.

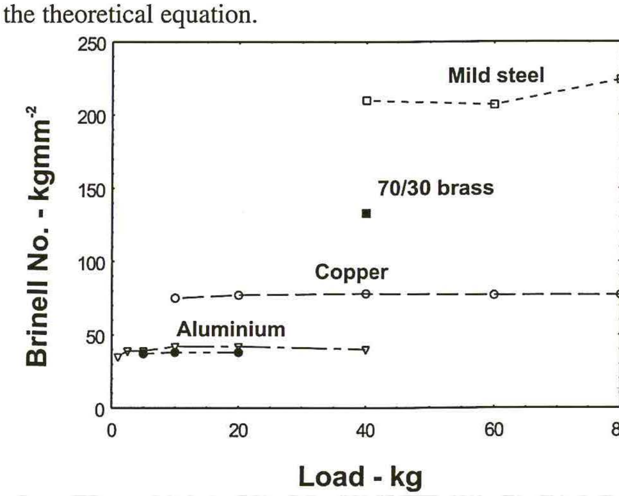

Fig.5 Brinell tests on flat plate specimens.

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Weighted Drop Tests

A 1.94mm diameter steel ball held captive in a Brinell tup, see fig.2, was used to produce indents in mild steel plate. Drop heights from 31 to 455mm were used giving mean indent diameters ranging from 0.326 to 0.704mm (means of five indents at each height). The measured values are presented in fig.6 together with a fitted curve. Again a best-fitting fourth root equation is a reasonable fit. The mass of the ball-plus-tup arrangement was 17.95g.

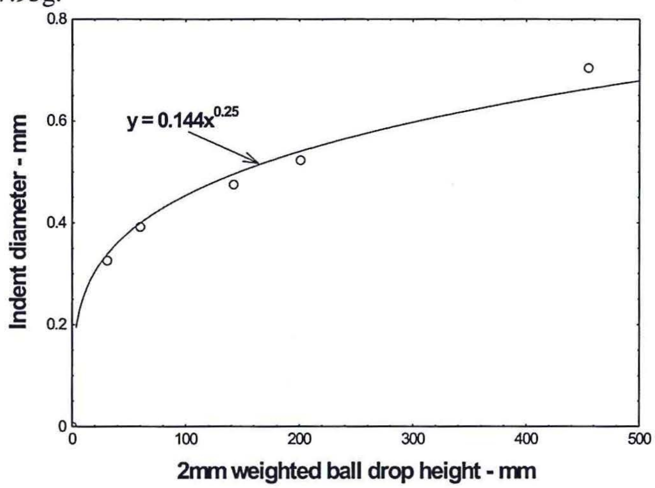

Fig.6 Effect of drop height of weighted steel ball on indent diameter induced in mild steel.

Comparison of Actual and Predicted Indent Diameters

The equation previously proposed for predicting indent diameters was:

$$d = 1{\cdot}278.D.P^{0.25}\ .\rho^{0.25}.v^{0.5}/B^{0.25} \qquad (2)$$

where d = indent diameter, D = indenting sphere diameter, P = proportion of kinetic energy lost on impact, ρ = density of indenting sphere, v = sphere velocity and B = Brinell hardness of component.

The following examples illustrate the difference between actual and predicted indent diameters.

Example 1. A 17.46mm diameter steel ball having a density of 7,860 kgm^{-3}, dropped from a height of 200mm onto mild steel plate gave P equal to 0.75. The ball had a deduced impact velocity of 1.98ms^{-1} and the mild steel plate had a Brinell strength of 213.7$kgmm^{-2}$. Substituting these values into equation (2) gives a predicted indent diameter of 1.286mm. That is rather larger than the measured value of 1.064mm.

Example 2. A Brinell tup having a mass of 17.95g was dropped from a height of 201mm onto the same steel plate as for example 1. The tup carried a 1.94mm diameter ball bearing. The mass of the tup gave an 'equivalent impact velocity' of 46.3ms^{-1} (compared with the 1.98ms^{-1} of an unweighted ball dropped from 201mm). Substituting these values into equation (2) together with P equal to 0.75 gives a predicted indent diameter of 0.691mm. That is also larger than the measured value of 0.523mm.

DISCUSSION

These studies have shown that precise control over the factors influencing indent diameter can be achieved using simple procedures. 'Full factorial' experimental work covering a range of values for all of the factors involved would require millions of measurements. A necessarily limited number of measurements have been presented here. They confirm, however, the predicted variations of indent diameter with indenter diameter, velocity, density and the Brinell strength of the target material.

Equation (2) consistently predicts a rather larger indent diameter than is observed in practice. That is because it assumes that the energy absorbed on impact is just as efficient in generating an indent as is a Brinell indenter. It is reasonable to suppose that with dynamic impact (rather than the almost static impact of Brinell indentation) a much larger proportion of the energy absorbed will be translated into elastic/heat energy. Examining the available data indicates that only one-third of the absorbed kinetic energy is used effectively. Equation (2) can be modified empirically to become:

$$d = 1{\cdot}278.D.(\tfrac{1}{3}P)0.25\ .\rho 0.25.v0.5/B0.25 \qquad (3)$$

Applying equation (3) to a wide range of experimental data shows a very good correlation between predicted and actual indent diameters. It must be noted, however, that as shot peening progresses indent diameters will become smaller. That is because the peened surface is becoming progressively work-hardened.

There are several practical advantages to being able to predict and analyse indent diameters. For example, we can estimate impact velocities and variations in impact velocity - knowing the average diameter and density of the particles being used and the Brinell strength of the test block material. •