

Prediction and Control of Indent Diameter

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INTRODUCTION

Shot peening control is based on satisfying two specified parameters – PEENING INTENSITY and COVERAGE. Peening intensity is independent of the component's properties, being defined by the reaction of Almen strips. Coverage, on the other hand, is a component-specific parameter in that a defined percentage of the component's surface should be covered with at least one indentation. Indent diameter connects both parameters. The larger the average indent diameter the greater will be both the peening intensity and the coverage (for a given number of indents). It follows that control of the indent diameter allows control of both of the specified parameters.

The controllable variables that influence indent diameter are well-known to shot peeners. They are shot diameter, shot velocity and shot density. These variables influence three interrelated factors: the volume of the indent, V, the amount of work done by the shot particle, W, and the amount of work, B, that has to be done to create each unit of indent volume. This article presents an equation that allows indent diameter to be predicted using known values of shot peening variables. A simple equation connects the three factors:

$$\mathbf{V} = \mathbf{W}/\mathbf{B} \tag{1}$$

As a 'hole digging' example for equation (1), if W represents 80 man-hours of work and B represents a situation where 10 man-hours of work are needed to create 1 cubic metre of hole then 8 cubic metres of hole are created. Simple geometry could convert the 8 cubic metres into an indent of a given radius.

VOLUME OF INDENT, V

The volume, V, of an indent, in the shape of a spherical cap, can be expressed as:

$$V = \pi \cdot d^4 / 32D + \pi \cdot d^6 / 64D^3$$
 (2)

where d is the indent diameter and D is the ball diameter, see fig.1.



The second term in equation (2) is so small that it can be ignored, giving the simpler relationship:

$$T = \pi \cdot d^4/32D \tag{3}$$

WORK DONE BY SHOT PARTICLE, W

V

A flying shot particle has a kinetic energy, E, given by the familiar expression: $E = 1/2 \dots v^2$, where m is the mass of the moving sphere and v is its velocity. Mass is volume, $D^3.\pi/6$, multiplied by density, ρ , so that for a sphere of diameter, D:

$$m = D^3 \pi . \rho/6 \tag{3}$$

Hence:

1

$$E = D^3 . \pi . \rho . v^2 / 12$$
 (4)

A proportion, P, of the kinetic energy, E, of the impacting particle is used as the work, W, needed to produce an indent. Some kinetic energy is retained as the particle bounces from the component's surface. The proportion retained is e^2 , where e is the coefficient of restitution. Hence $P = (1 - e^2)$. As an example, if e = 0.8 then P = 0.36 meaning that only 36% of the energy of the impacting sphere is transferred to the component's surface. Now since W = P.E and using the value for E from equation (4) we have that:

$$W = (1 - e^2) \cdot D^3 \cdot \pi \cdot \rho \cdot v^2 / 12$$
(5)

WORK DONE PER UNIT VOLUME OF INDENT, B

The work done per unit volume of indent, B, is much larger than the work done in either pure tension or in pure compression, C.

Consider first the work, C, needed to produce pure compression. Fig.2 shows a short cylinder that has its height reduced by an amount, h, when a force, F, is applied. This is the situation in classic compression testing. In the sense that an indent is a space created that was previously occupied by solid, the dashed region shown in fig.2 (b) can be regarded as being equivalent to a disc-shaped 'indent'. Material below the indent is coldworked. The work done per unit volume C is simply the compressive yield strength, Y. That is because C is given by F·h/(h·area), which reduces to F/area, which is the applied compressive stress, Y. Hence we have that C = Y.

Indentation of a relatively-large block by a reasonablyspherical particle is not the same as pure compression. Metals are virtually incompressible, so that the volume must remain constant. With the isolated cylinder shown in fig.2 the diameter, d, increases during the formation of the 'indent' in order to maintain constant volume. There is no restraint, other than air pressure, to this expansion of diameter. The region below an indenting sphere, on the other hand, is restrained by the surrounding block of material. This gives rise to three-dimensional

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compressive stressing (see later section). Much more work has, therefore, to be done, per unit volume of indent, than would be predicted by simply using the uni-dimensional compressive yield strength. The actual work done is the 'indent strength', B,

of the material. Indent strength, B, (work done per unit volume of indent) can be equated directly with the Brinell hardness of the material being indented. The derivation of work done per unit volume is slightly more complicated than it is for pure compression of a cylinder. The force, F, during indentation is initially zero and builds up linearly with increasing indentation depth until it reaches a maximum, say Fmax. The average force during indentation is therefore $F_{max}/2$ so that the work done is $F_{max} \cdot h/2$. Indent area also varies from zero (on initial contact of sphere and component) to a maximum, say A, with the average indent area being A/2. The volume of the indent is therefore given by $A \cdot h/2$. Dividing work done by volume of indent is then simply Fmax /A which is the Brinell hardness value. To find the indent strength for a material in a given condition (of cold work or heat treatment) we can either look up, or measure, the Brinell hardness. It is important to use standard units. Brinell hardness is normally quoted in kgf/mm² which must be multiplied by 9.8 to convert to MPa. A Brinell hardness value for mild steel of 200 (kgf/mm²), for example, becomes 1,960MPa. That is several times the yield strength of mild steel in pure compression.

In summary the amount of work that has to be done to create each unit of indent volume is equal to the Brinell hardness value, B.

EQUATION FOR INDENT DIAMETER PREDICTION

Substituting the values for V and W, given by equations (3) and (5), into equation (1) gives:

 $\pi \cdot d^4/32D = (1 - e^2)$. D³. π . ρ . $v^2/12$ or d⁴ = 8.D⁴.(1 - e^2). ρ . $v^2/3B$ which, on taking 'fourth roots' gives:

$$\mathbf{I} = \mathbf{1} \cdot \mathbf{278} \ \mathbf{D} \cdot (\mathbf{1} - \mathbf{e}^2)^{0.25} \cdot \mathbf{\rho}^{0.25} \cdot \mathbf{v}^{0.5} / \mathbf{B}^{0.25}$$
(6)

where d = indent diameter, D = indenting sphere diameter, e = coefficient of restitution, ρ = sphere density, v = sphere velocity and B = Brinell hardness of component.

Substitution of known values for the variables in equation (6) is straightforward provided that consistent units are used. $\rho^{0.25}$.v^{0.5}/B^{0.25} is 'dimensionless', i.e. the units used cancel one another. We can use conventional values for ρ in kgm⁻³ and velocity in ms⁻¹ if Brinell hardness is in Nm⁻². In order to convert kgf.mm⁻² into Nm⁻² (Pa) we multiply by 9.8 x 10⁶. For example, a published (or measured) value for Brinell hardness (H_B) of 200kgf/mm² becomes B = 200 x 9.8 x 10⁶ Nm⁻² (equivalent to 1960MPa).

Example:

A 0.1mm diameter steel sphere (density 7860 kgm⁻³) moving at 40ms⁻¹ strikes a steel plate that has a Brinell hardness of 200kgf/mm⁻². The coefficient of restitution is 0.71. Substituting into equation (6) gives a predicted indent diameter, d, of:

 $d = 1.278 \text{ x } 0.1 \text{mm x } (1 - 0.71^2)^{0.25} \text{ x } 7860^{0.25} \text{ x}$ 40°5/(200 x 9.8 x 10⁶)°25 so that

d = 0.026mm.

APPLICATIONS OF INDENT EQUATION

The indent equation, (6), contains three variables – shot diameter, shot density and shot velocity – that are controlled by the shot peener. The two remaining variables – Brinell hardness and coefficient of restitution – are properties of the component material. Fig.3 shows the relationships between indent diameter and four of the variables. The "magnitude of variable" is shown as varying by an order of magnitude (1 to 10), which covers the range found in most peening plants.





The effects of changes in coefficient of restitution are not shown in fig.3 since the value of the parameter is rarely known. For most component materials the value of $(1 - e^2)$ will vary between 0.4 and 0.6, so that assuming a value of 0.5 will only introduce a very small error. The effects shown in fig.3 are based on assuming that only one variable is changing at a time. Shot diameter clearly has the greatest effect followed by shot velocity. Shot density and component Brinell hardness have relatively small, but opposite, effects on indent diameter.

THREE-DIMENSIONAL COMPRESSION

A triaxial compressive stress system exists for the component material being deformed by a shot particle. Triaxial stressing is illustrated in fig.4. Principal stresses of 5Y, 4Y and 4Y, are shown as acting on a representative cube of component material situated under the indent. The principal stress values chosen are simply indicative. The stress normal to the surface must be greater than the two that are parallel to the surface. These two parallel-to-the-surface stresses will be equal in magnitude.

The conditions for plastic deformation are given by a 'yield criterion'. Tresca's yield criterion states, "The difference between the largest and smallest principal stresses equals the yield strength". The stress system of fig.4 satisfies that criterion because (5Y - 4Y) = Y. It would also satisfy the more complicated Von Mises yield criterion. In effect, in this example we have to apply a 'vertical' (or peening) stress that is much larger,



5Y cf Y, than it would be in the absence of the constraining 'horizontal' stresses. These constraining stresses are due to the material resisting being pushed. The need to satisfy a yield criterion is why the Brinell strength is so much larger than the corresponding yield strength in uniaxial compression for the same material.

The general "State of Stress" under an impacting shot particle can be expressed as (Y, 0, 0) + (Q, Q, Q), where Y is the uniaxial compressive yield strength and (Q, Q, Q) is the hydrostatic compressive stress component. It is this hydrostatic compressive stress component that allows very large plastic deformations to occur during peening (as well as in such processes as extrusion).

DISCUSSION

Brinell indentation is a close simulation of peening indentation as it (a) incorporates both the triaxial stressing common to both processes and (b) is carried out at a reasonably-high velocity (very much higher than with tensile testing). 'Low-load' Brinell testing can be carried out using an adapter fitted to a standard Vickers hardness tester. These adapters use either a 1mm or a 2mm diameter ball (rather than the 10mm diameter 'industrial' Brinell indenter) with correspondingly low applied loads. A common form of adapter has the facility for changing the indenting balls – they wear quite quickly! That facility also allows experiments to be carried out using different indenting materials, such as ceramics, cermets and even glass.

Real shot streams will contain a range of shot particle diameters, spread about some average diameter. This average diameter can be used for estimating average indent diameter and hence average indent area. It is to be expected that there will be a smaller spread (standard deviation) of indent diameters than there will be of particle diameters. That is because particles smaller than the average will normally be accelerated to higher velocities than particles that are larger than average.

Indent diameter and coverage are the primary variables in shot peening. It follows that control of these two factors is of fundamental importance in exercising effective peening control. An ability to predict the indent diameter can therefore be very useful. Experimental studies, designed to assess the accuracy of the indent equation presented here, will form the basis of a future article. Preliminary experimental findings are encouraging.