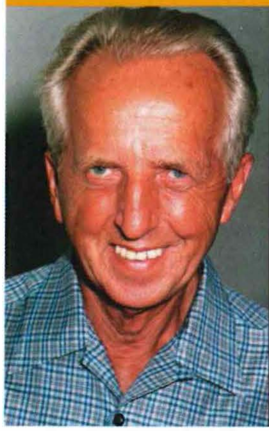

Morphology of Shot Peening Indentations

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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 laboratories. He is currently writing a book "The Science of Shot Peening". We greatly appreciate his contribution to our publication.

Introduction

'Morphology' is the science of shape. Shot peening necessarily involves the production of indentations in the component's surface. This article is concerned with the morphology of those indentations. The isolated indentations that are present in the early stages of peening have simple shapes. We can then apply classical geometrical procedures to quantify the shape parameters. Progressively, the indentations overlap and the morphology becomes correspondingly complex. Individual indentation identities become subsumed into a general picture of multiple deformations.

Attention is concentrated here on the morphology of individual indentations. These are analysed in terms of the indentations themselves and surrounding displaced material - 'ridges'.

A convenient starting point is to consider the indentations made by perfectly spherical shot particles striking the flat surface of an isotropic plastic material at 90°. Immediately there is a difficulty! Where does the material go to that 'disappears' when the indentation is formed? Two extreme possibilities are (i) that only a perfect 'spherical cap' is formed in the surface and (ii) that all of the indentation material is thrown up as a surrounding ridge. Fig.1 shows the two possibilities as 'A' and 'B' respectively.

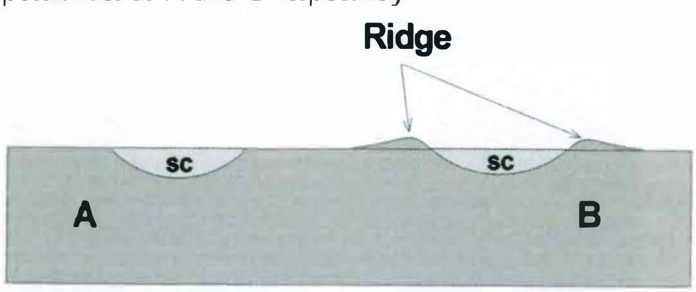

Fig.1 Indentation as spherical cap, sc, as at A, and with surrounding ridge as at B.

The first possibility would require that the macroscopic shape of the peened object must change — as shown in Fig.2. This type of macroscopic shape change is found in both peen forming and the bending of Almen strips induced by peening.

Spherical Caps

'Spherical cap' is simply a geometrical term used to describe a 'slice' taken from a sphere. Using this term we can readily access available information, e.g. at the web site www.Mathforum.org.

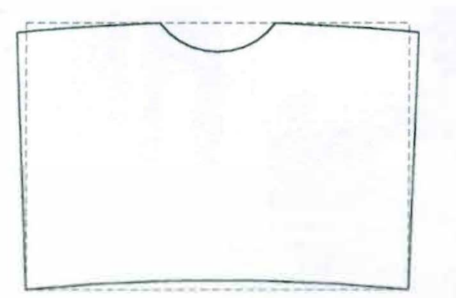

Fig.2 Plastic distortion to accommodate material displaced from indentation.

Fig.3 shows a representation of a 'spherical cap' indentation formed in a flat surface by a spherical shot particle. The relevant parameters are: the radius, R, of the particle, the depth of the indentation, h, and the radius of the indentation, r.

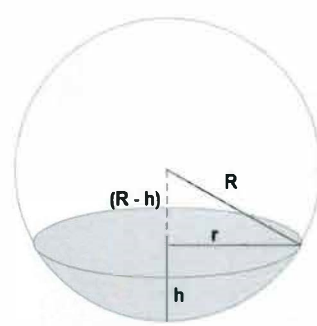

Fig.3 Parameters of spherical cap indentation.

The three parameters, R, r and h are interdependent. Hence, if we know the magnitude of any two of the parameters we can deduce the value of the third. The inter-relationship is given by the simple Pythagorean equation:

$$R^2 = r^2 + (R - h)^2 \qquad (1)$$

Probably the most significant geometrical features of a spherical cap are its volume, V, and surface area, S. These are given by the following equations:

$$V = (\pi/6)(3r^2 + h^2)\,h \qquad (2)$$
$$S = 2\pi \cdot R \cdot h \qquad (3)$$

The usefulness of equations (1) to (3) can be illustrated by the following student questions:

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Q1 What is the approximate depth of an indentation made by a 600μm diameter spherical shot particle when the diameter of the indentation is 200μm?

Q2 What is the percentage increase in surface area for the indentation of Q1? Comment on the significance of the area increase.

A1 The solution of Q1 starts with equation (1). Two of the three variables are given (R and r) so that we must be able to solve for the one remaining unknown variable, h. Rearranging equation (1) gives that:

$$h^2 - 2\pi \cdot R \cdot h + r^2 = 0 \qquad (4)$$

Substituting the given values for R and r into equation (4) and solving for h yields that:

$$h = 17.157\mu m$$

or approximately 17μm

A2 The original surface area that has been indented, A_i, is given by $A_i = \pi \cdot r^2$. The area of the spherical cap, S, is given by equation (3) as $S = 2\pi R h$. We know from the previous answer that h = 17.157μm and we are given the values of R and r (300 and 100μm respectively). Hence we have (in micrometers):

$S = 2 \cdot \pi \cdot 300 \cdot 17 \cdot 157$ or $S = 32{,}340\mu m^2$ and
$A_i = \pi \cdot 100^2$

or $A_i = 31{,}416\mu m^2$

The increase in area $[100(S-A_i)/A_i]$ is therefore **2.9%.** That value compares with the maximum feasible increase (that occurs when the indentation is a hemisphere) of **100%.**

A consequence of area increase is that we are creating nascent metal surface. All except precious metals are covered with a brittle protective oxide - formed by exposure of any nascent (new) surface to the oxygen in the atmosphere. If we now indent a metal component, the nascent surface area produced must now oxidise. The previously oxidised surface is expanded so that extensive cracking will have to occur in order to allow the nascent areas to be formed. This will not normally be a practical problem as the protective oxide layer is extremely thin. The percentage increase in surface area would be greater if a ridge was formed in addition to the spherical cap indentation. Overall, however, the increase in surface area is small so that any surface features (such as scratches) would not be affected substantially.

Ridges surrounding Spherical Cap Indentations

The ridge zone surrounding a spherical cap indentation can be quantified. Fig.4 shows a representation of a ridge similar to one that has appeared in the technical press.

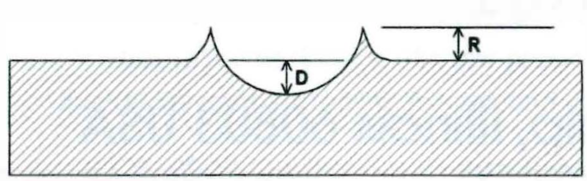

Fig.4 Representation of shot dimple, depth D, with ridge of height R.

In fig.4 the ridge height, R, is presented as being similar in magnitude to the dimple depth, D. The ridge is presented as being sharp-topped. There are then, three features of immediate interest:

1. Sharpness of the ridge top.
2. Volume of the ridge relative to the volume of the spherical cap indentation.
3. Shape of the ridge, which appears in fig.4 as a close approximation to an isosceles triangle.

1. If the sharpness illustrated in fig.4 did appear in practice then it would be extremely worrying. Sharp ridge tops would be folded over by subsequent impacts, generating a multitude of defects in the peened surface. There does not seem to be any theoretical reason to explain how sharp-topped ridges could be generated. The kinetic energy vector for shot particles striking a component s surface at 90° is also perpendicular to the surface. During formation of the spherical cap, there will be lateral components of force, between particle and component surface, pushing material sideways—but not upwards.
2. The volume of any ridge can be estimated using simple procedures - if we simplify the cross-section of the ridge. By definition an 'estimation' does not require the answer to be exact. A good estimate should, however, give a value that is close to what one would accept as the exact answer. For the purposes of the following estimates, it is assumed that a triangle should give a good approximation to the cross-sectional area of a ridge. The ridge shown in fig.4 can, for example, be approximated as an isosceles triangle whose altitude (perpendicular height) is the same as its base. That may be considered a special example of a general model of a ridge. A general model is illustrated in fig.5 where the ridge cross-section has a superimposed scalene triangle. The triangle has a centroid at O, which is always at a distance, R, from the central axis of the spherical cap, R being the radius of the shot particle. This general model ensures that the volume of the ridge, V, is simply the centroid peak circumference, 2πR, multiplied by the cross-sectional area, A, of the triangle representing the ridge. Hence:

$$V = 2\pi R \cdot A \qquad (5)$$

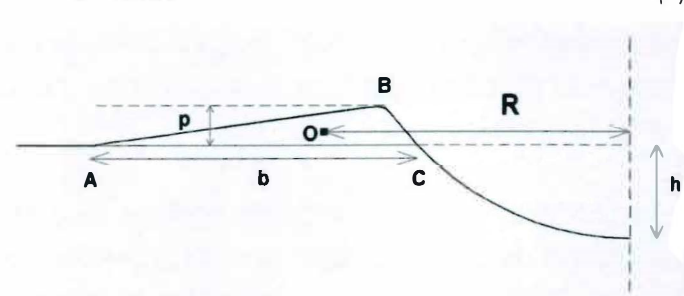

Fig.5 Ridge with superimposed triangle ABC having base, b, perpendicular height, p, and with its centroid O at a distance R from a spherical cap indentation of depth, h.

The ridge in fig.5 assumes a near-triangular shape. Equations (2) and (5) can be used to compare the volumes of the ridge and the spherical cap indentation for various real or imagined ridge shapes. The following calculations are based on the ridge shapes given in figs. 4 and 5. Values for the parameters required were obtained from magnified drawings. The objective at this stage is simply to get a feel for the relative volumes using assumed (rather than real, measured) ridges.

Fig.4 The ridge cross-section can be approximated to an isosceles triangle having a base 6 and a perpendicular height 7 (drawing units) giving an area of 21. The indentation has a depth of 7 units and the shot radius, R, is 16. Substitution into equation (4) gives that $r^2 = 175$. Hence:

Volume of ridge, $V_R = 2*\pi*16*21$ or

$V_R = 2111$

Volume of cap, $V_C = 7*\pi(3*175 + 49)/6$ or

$V_C = 2104$

These values show that the volume of the proposed ridge is equal to that of the indentation (to the nearest significant unit).

Fig.5 The ridge cross-section can be approximated to a scalene triangle having a base 24 and a perpendicular height 3 (drawing units) giving an area of 36. The indentation has a depth of 7 and a radius r of 16. Substitution into equation (4) gives that the shot radius, R, is 22. Hence:

Volume of ridge, $V_R = 2*\pi*22*36$ or

$V_R = 4976$

Volume of cap, $V_C = 7*\pi(3*256 + 49)/6$ or

$V_C = 2994$

These values show that the volume of the proposed ridge is about 170% of that of the indentation. The calculations given above indicate that the ridge proposed in fig.5 has an exaggerated cross-sectional area.

Experimental Studies of Indentations

There is a paucity of published information about the profile of the areas surrounding individual indentations induced by shot peening. For the purposes of this investigation large indentations were produced. Large indentations magnify the dimensions of the corresponding ridges, making them easier to measure. Photographs were produced using a digital camera, optical coupler and standard bench microscopes.

A large indentation was produced by pressing a 12.7mm diameter ball bearing into a scratch-brushed aluminum block. The indentation had a diameter of 6.4mm with a calculated indentation depth of 0.86mm (calculated using equation 1). A macro photograph of the 6.4mm diameter indentation is shown as fig.6.

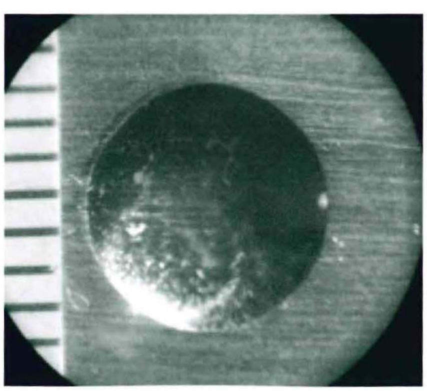

Fig.6 Macro photograph of 6.4mm diameter indentation in aluminum made with a 12.7mm diameter ball bearing. A millimetre scale is shown on the left side of the indentation.

A surface profile was produced for the 6.4mm diameter indentation; using standard surface profiling equipment, see fig.7.

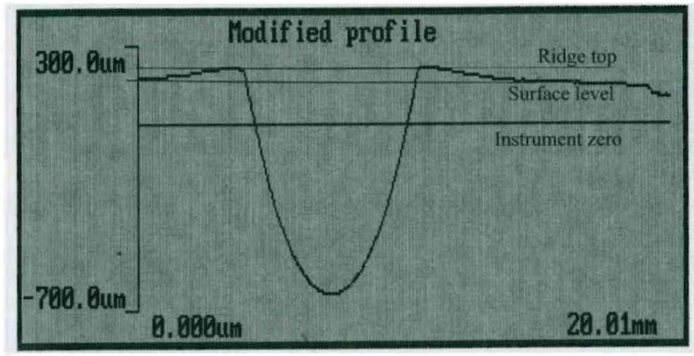

Fig.7 Talysurf trace of indentation made by 12.7mm diameter ball bearing pressed into an aluminum block.

The trace was carried out over a distance of 20.0mm with vertical sensitivity of the laser head set to give a full-scale deflection of 1.000mm. Hence, the shape of the indentation shown in fig.7 is distorted to appear parabolic. Measurements from the trace indicate that the depth of the indentation at surface level is 0.81mm rather than the calculated 0.86mm. The difference could be partly attributed to ball flattening, with the remainder caused by lateral movement of the ball bearing during pressing. Alternatively the single trace might not have passed through the exact centre of the indentation. More importantly, the trace gives a clear indication that the ridge profile is close to that shown in fig.5 and does not involve a sharp peak as shown in fig.4. Further measurements from the trace indicate that the ridge is 0.05mm high by 4.0 to 4.5 wide giving a cross-sectional area in the range of 0.10 to 0.11mm². The mean ridge radius lies within a range of 4.0 to 4.5mm. The volume of the ridge, V, can be estimated using a modification of equation (5):

$$V = 2\pi R_M \cdot A \qquad (6)$$

where R_M is the measured ridge radius and A is the measured cross-sectional area

Substituting the measured values into equation (6) gives a range from 2.5mm³ to 3.2mm³ for the ridge volume. The volume of the indentation calculated using equation (2) is 13.3mm². Hence, the ridge volume is some **19 to 24%** of the volume of the indentation.

With a 6.4mm diameter indentation created by a 12.7mm diameter ball the area increase is from 32.17 to 34.52mm². This is a **7.3%** increase of the surface area - stretched to form the indentation. Fig.8 shows that the original scratches have only been slightly smoothed during the indentation of aluminum by a highly-polished 12.7mm diameter ball bearing.

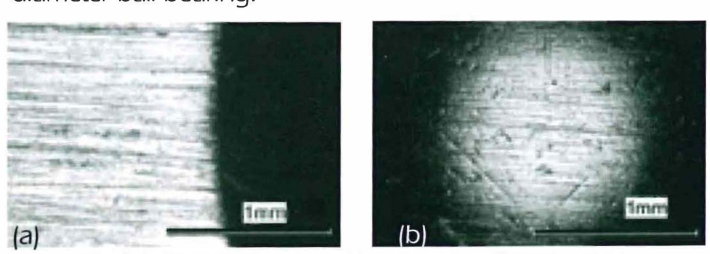

Fig.8 Indentation edge, (a), and centre of indentation, (b) at identical magnifications.

Discussion and Conclusions

There are two important aspects to this analysis of indentation morphology. The first is that a small proportion of the displaced material is converted into a shallow, wide, ridge surrounding the indentation. The second is that each indentation creates a small increase in the surface area of the component.

A general model of the ridge surrounding shot peening indentations is shown in fig.9.

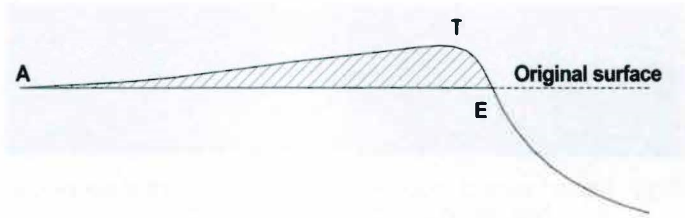

Fig.9 General model of ridge surrounding peening indentation.

The model envisages a round-topped peak at T, close to the indentation edge, E, tapering gradually to merge with the original surface at A. The height of the peak is only a small fraction of the depth of the indentation. Although only a single, large, indentation has been quantified in this paper, the model is in agreement with numerous studies made on a range of shot-peened materials. No evidence was found in those studies of sharp-topped ridges. It should be noted that a uniform ridge around an indentation depends upon the shot particle having struck the surface at 90°. Striking the surface at angles produces non-uniform ridges. The effect of impingement angle on both morphology of indentations and on Almen saturation curves is examined in a separate paper (D. Kirk and R. C. Hollyoak - to be published). The ratio of the volume of ridge material to volume of indentation would be expected to depend upon the geometry of the component. Rigid components, such as thick blocks, would offer more resistance to shape change so that the ratio could be greater than for thin components such as sheets. Even with thick blocks it is argued that most of the indentation volume contributes to shape change rather than to ridge formation.

It has been shown that a small increase in surface area occurs when each indentation is produced. The maximum increase, for a hemispherical indentation, is 100% but real peening situations will normally involve increases of less than 10%. It should be remembered that, with high levels of coverage, individual points on the component's surface may have been impacted a large number of times. Hence, the total stretching of the original surface layer can easily exceed 100%.