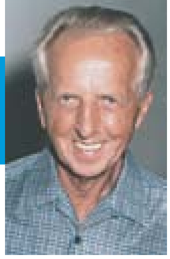

ACADEMIC STUDY
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Peening Impressions (Dents)

INTRODUCTION

The SAE specification J2277 on coverage mentions "overlapping peening impressions (dents)." That specification also includes "Coverage is defined as the percentage of a surface that has been impacted at least once by the peening media." The only evidence that a surface has been impacted is the peening impressions (dents) left by the impacts. It is therefore somewhat surprising that there is no corresponding definition of a peening impression (dent).

Peening impressions (dents) are the "be all and end all" of shot peening. They govern not only coverage but also residual stress generation, surface work hardening, distortion/peening intensity, oxide removal and roughening/smoothing of components.

A previous article in this series (*The Shot Peener*, Spring 2003 "Morphology of Shot Peening Indentations") considered the scientific features of indentations. This article aims to complement that article. Individual and overlapping dents are considered as separate issues.

INDIVIDUAL DENTS

Mechanics of Dent Creation

A small proportion of a shot particle's kinetic energy, ½mv^2, is converted into plastic deformation when it impacts a component. The impact therefore generates a dent whose shape depends on the shape of the shot particle and whose magnitude depends on the amount of energy conversion. An important relationship is that:

"Kinetic Energy and Work Done have the same units and are therefore directly interchangeable."

The units for kinetic energy are kg.m^2.s^{-2}. Work done is force times distance – but force is mass times acceleration. Hence work units are kg.m.s^{-2}.m or kg.m^2.s^{-2} – the same as for kinetic energy. Fig.1 represents the work being done as a spherical impacting particle strikes a flat surface.

Initially the shot particle has zero contact area so that the force (stress times area of contact) must also be zero. With further penetration the area of contact grows and with it the force being exerted but stress is maintained at the yield strength of the component. When the particle reaches its maximum penetration both the contact area and the yield strength are at a maximum – hence we have maximum force. Thereafter plastic deformation ceases and the particle rebounds due to the stored elastic energy below the dent. At final contact the dent has a diameter **D1**.

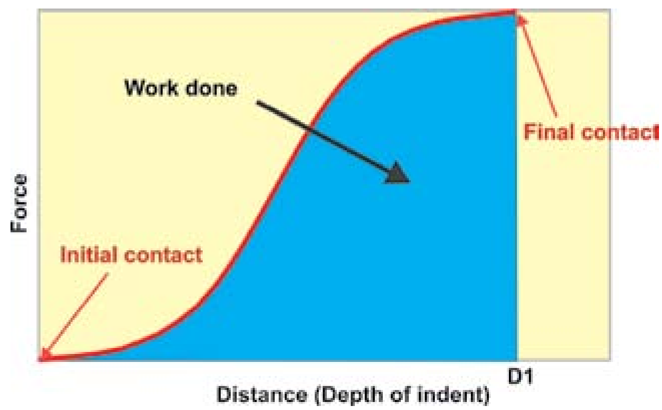

Fig.1. Work done during creation of an individual dent.

Geometry of a Direct Impact Dent

During impaction the component metal must move in order to generate the dent – it does not evaporate or become fragmented. The material of the indentation has to go somewhere! Each dent has two components: indentation and ridge. These components are illustrated by fig.2 which models a 90˚ impact. The indentation then has the geometrical shape of a 'spherical cap' whereas the ridge approximates to the geometrical shape of an annular ring. The volumes of the indentation and ridge components are not equal to one another. That is because there are two mechanisms whereby the indentation material can be moved: **outflow** and **upflow**. Outflow contributes to the distortion of a component whereas upflow generates the ridge. If outflow predominates, as in the case of thin strip material, then the distortion effect predominates and the ridge component becomes less noticeable. Conversely, for relatively thick components the ridge region becomes more noticeable.

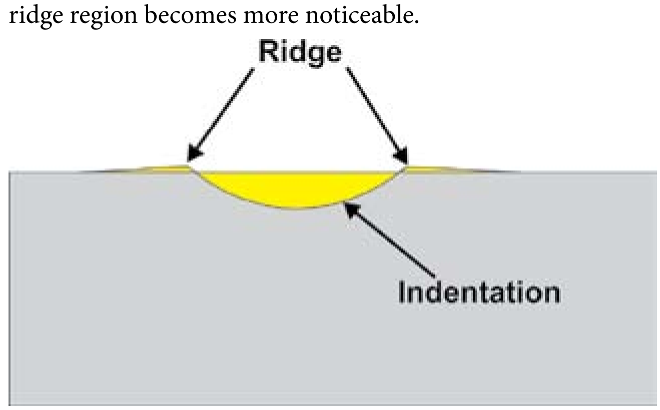

Fig.2. Cross-section of a peening impression (dent).

Outflow of Material during Impaction

Fig.3 represents a thin elementary disc where the outflow component is imagined to be 100% of the total flow. Outflow is not uniform – it is easiest at the extreme surface and becomes more difficult below the surface (setting up the resistance that generates compressive residual stress). An original flat disc therefore assumes a curvature because of the outflow of a peening indentation (dent). The average outflow strain, **ε**, varies with the radius of the impacting sphere, **r**, the depth of the indentation, **h**, the thickness of the disc, **t**, and the diameter of the disc element, **D**. Equation (1) quantifies these factors.

$$\varepsilon = 2*h^2*r/(t*D^2) \qquad (1)$$

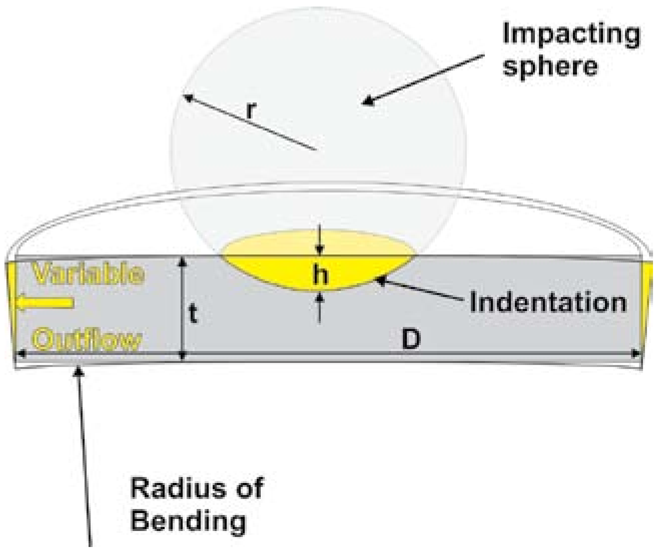

Fig.3. Model of variable outflow generating curvature of a disc element.

Equation (1) can be used to predict the magnitude of plastic expansion induced by a single indentation. For example, assume **h** = 0.1mm, **r** = 0.5mm (S230 shot), **t** =1.3mm (A strip) and **D** =1.754mm. Substitution in equation (1) predicts a plastic strain of 0.0025 (0.25%). An Almen A strip with an arc height of 0.254mm (0.010") has a radius of 256mm. If this was induced solely by plastic bending then the surface strain would be precisely 0.0025 – the same as predicted for pure outflow (using the assumed indentation values). This example only indicates that pure outflow predicts similar plastic strains to those that are actually observed.

Upflow of Material during Impaction

The second mechanism of material movement is upflow - to form a ridge around the indentation. Material movement then has several similarities to those associated with a tsunami. For a tsunami there is a sudden displacement of a large volume of water leading to a wave that has small amplitude and very long wavelength. Fig.4 represents just two stages of ridge formation. In the early stages of indentation, A, a tiny ridge is created by upflow of plastically-deforming component material. As indentation progresses this is squeezed outwards and grows continuously towards the final stage B. Throughout the process there is continual upflow of component material.

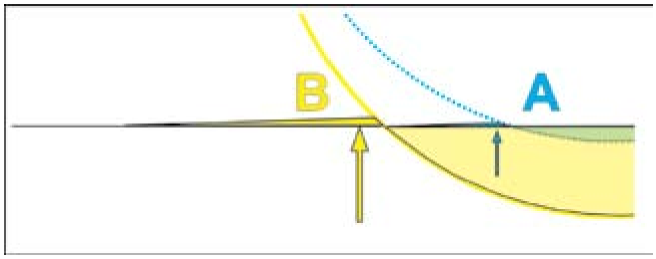

Fig.4. Early and final stages of annular ridge formation.

The shape of the annular ridge is similar to that of a modified scalene triangle (a triangle with three unequal sides). Some modification is required in order to accommodate the curvature of the impacting sphere and the established flow characteristics of metals. Fig.5 shows the cross-sectional shape of a typical annular ridge.

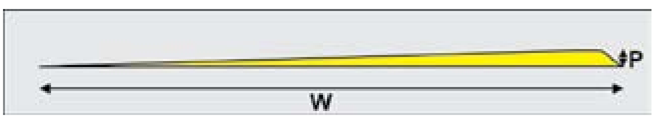

Fig.5. Cross-section of a typical annular ridge caused by upflow of component material.

Measurements have shown that typical annular ridges have a volume about 19 -24% of that of the indentation, a width, W, about half the diameter of the indentation and a height, P, about 15% of the indentation depth. The relatively-large width of the ridge matches the plastic deformation zone that surrounds every indentation. That zone has been shown to have twice the diameter of the actual indentation.

Individual Dent Created by Angled Impact

Shot particles striking a flat surface at an angle create an elliptically shaped indent. The depth of the indent is lower than for perpendicular impact by an equivalent shot particle. This therefore generates a lower peening intensity. As well as having an elliptical shape, the dent's ridge geometry is drastically different. The ridge becomes asymmetric, narrower and has much greater maximum height than occurs with perpendicular impact. Fig.6 is a schematic representation of the different situations.

Fig.6. Comparison of perpendicular and 45o dent ridges.

Angled-impact ridges only occur on one side of the dent – that for the direction of impaction.

Individual Dent Measurement

A central problem in dent measurement is to be able to identify its extent. The shortest side of the ridge's 'scalene triangle' cannot be distinguished from the indentation itself. It follows that most measurements on single indentations are of the diameter of the annular ring's peak. Fig.7 illustrates the situation when using a vertical collimated light beam. Rays are reflected from the surface of the indention in 'mirror fashion'. As the angle deviates from 90˚ less and less light is returned back into an eyepiece. The "high reflectivity" zone defines the apparent diameter of the indent. A substantial proportion of light is, however, reflected from the bottom of a spherical indentation – which can cause image analysis problems.

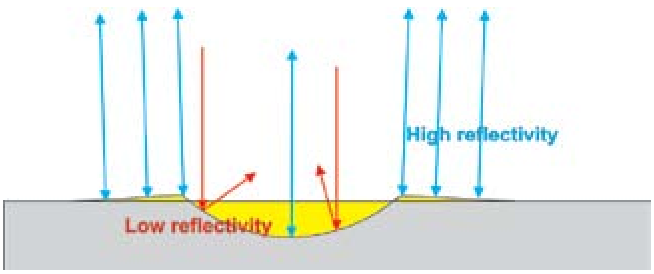

Fig.7. Variable reflectivity of a collimated light beam striking peening impression (dent).

Indent Aspect Ratio

Indent aspect ratio is the ratio of indent depth, d, to indent radius, r. Fig.8 represents the variation of aspect ratio for increasing shot particle penetration (but with ridge formation omitted for clarity).

The ratio d/r can vary between 0 and 1 (when the particle reaches the maximum feasible depth). In practice the aspect ratio for commercial shot peening is of the order of 0.1.

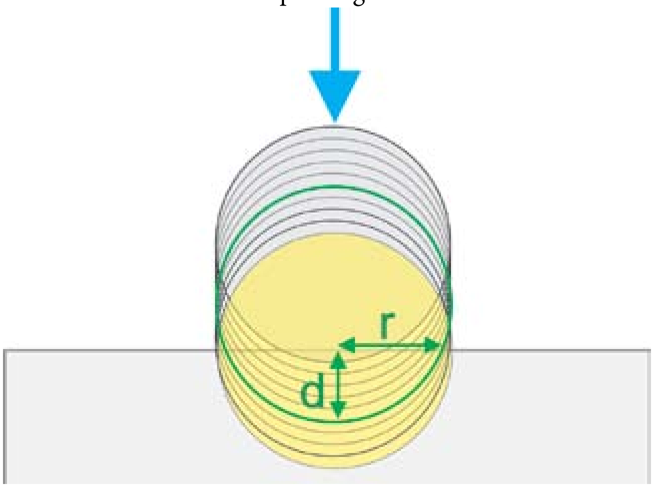

Fig.8 Variation of dent aspect ratio with increasing shot particle penetration.

As the dent aspect ratio increases so does the relative height of the surrounding impact ridge. This effect is represented in fig.9 – being similar to the effect shown in fig.6 except that the ridge is symmetrical. With a high aspect ratio the impact ridge surrounding the dent becomes dangerously high. That is because neighboring subsequent dents will introduce "peened surface extrusion folds."

Fig.9 Increase of impact ridge height with increase of indent aspect ratio.

OVERLAPPING DENTS

Coverage prediction programs are generally based on the assumptions that indents are circular and of constant diameter so that an overlapping indent has the same diameter as that of the one being overlapped. None of these assumptions are 100% correct. The diameter of an overlapping indent depends primarily on the degree of overlap.

Dents Involving 100% Overlap

The greatest degree of overlap is when a second impact coincides exactly with the first indent. This situation is illustrated in fig.10 (ridges being omitted for reasons of clarity).

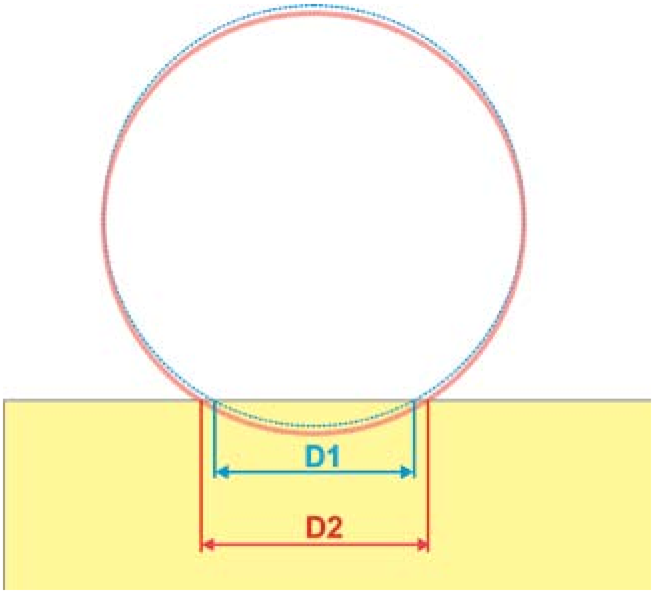

Fig.10. Increased dent diameter with 100% overlapping of second impact.

The generation of the work done during this second impact follows a very different path from that shown in fig.1. Fig.11 illustrates the work done and its effect on dent diameter. On initial contact the shot particle makes the same contact area as at the final contact stage of the first impact. Thereafter the force rises as both the area of contact and the degree of work-hardening increase. At final contact, when the particle starts to rebound, the dent has its diameter increased from **D1** to **D2** (see fig.10). Less plastic deformation work is done during the second impact because the underlying material has been work-hardened – which increases the fraction of elastic energy. Third and subsequent impacts on exactly the same center will produce smaller and smaller increments of diameter.

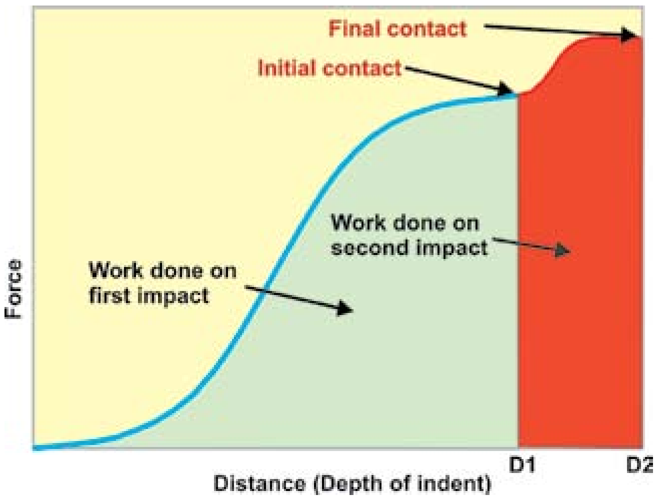

Fig.11. Progress of work done during second impact with 100% overlapping.

Dents with Less Than 100% Overlap

Dents with less than 100% overlap display a wide range of features – too complicated to analyze in detail here. Fig.12 illustrates the range of features produced at a low coverage level. The component material is polished mild steel – chosen because of its ability to display deformation zones around the dents.

When there is considerable overlap, as at A, asymmetric ridges are produced. These are similar to those produced by angled impact (see fig.6). Close inspection shows up the peaks of ridges as light-reflective regions with the remainder appearing to be shadows. With small overlapping, as at B, deformation is symmetrical.

It is impossible to determine the effect of degree of overlap on indent diameter using ordinary peening conditions. That is because particles have different diameters and impact velocities. Under laboratory conditions it has been found that: (1) as the degree of overlap decreases, the diameter of the second dent increases to a maximum and then decreases and (2) when the overlap just becomes zero then the second dent has the same diameter as the first dent. This second finding is surprising because the work-hardening associated with a first impact would have been expected to reduce the diameter of an adjacent second impact.

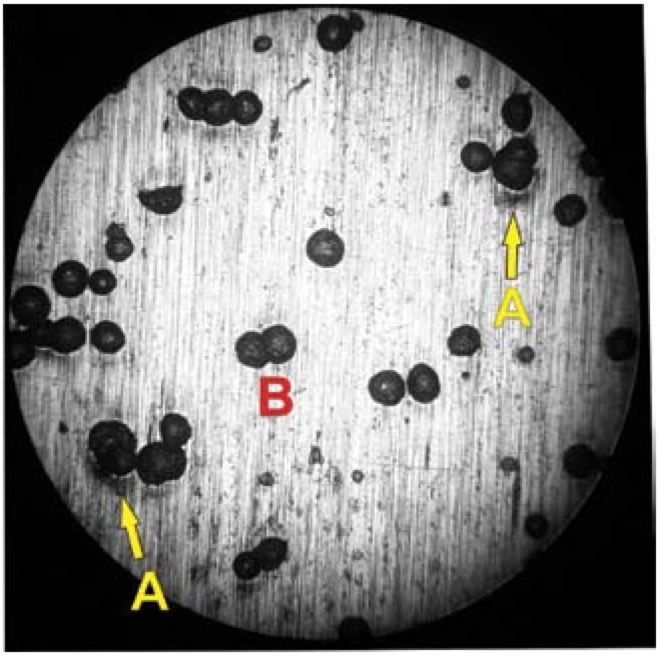

Fig.12. Range of effects associated with overlapping dents.

Peened Surface Extrusion Folds

Peened surface extrusion folds are known to detract from component service performance - normally. One exception might be for the case of surgical implants. Useful tissue growth could be enhanced by the presence of folds – analogous to enhanced seedling initiation on rocks.

Reduction of harmful extrusion fold formation is difficult. Wherever possible, angled impact should be avoided. Indent formation involves three-dimensional deformation mechanics with induced compressive stress parallel to the surface encouraging super-ductility – and hence fold formation.

STRESS STATE CHANGES DURING PEENING

Two important component factors change during shot peening:

Yield strength and
Residual Stress parallel to the surface.

Both of these factors affect the state of stress and therefore the size of induced dents. Fig.13 (page 32) represents (in two dimensions only) the state of stress for a representative tiny cube of component material. – i is the perpendicular compressive stress being imposed by the impacting shot particle, - q is the induced compressive stress resisting outward flow of material and – r is the induced compressive residual stress that develops as a consequence of the outward flow of material. The two induced compressive stresses combine to give a magnitude of – (q + r).

Fig.14 (page 32) represents all three stresses that make up the stress system that causes dent formation during impact.

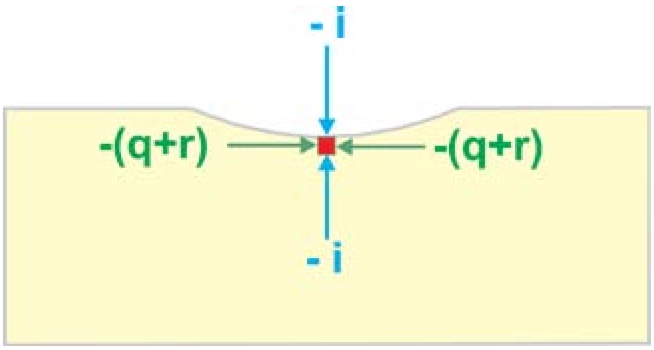

Fig.13 Stress state during impact showing two of the three orthogonal stresses.

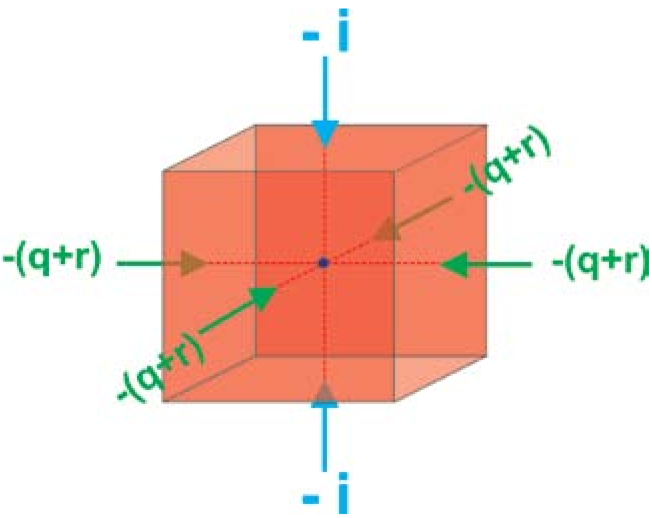

Fig.14 Three-dimensional stress system causing dent formation.

Application of a yield criterion shows that:

$$\mathbf{i = Y + (q + r)} \qquad (2)$$

Equation (2) is important. Stated in words it is that: The stress being imparted by the shot particle must reach the sum of the component's tensile yield strength plus the sum of the induced reaction stress and the induced residual stress.

As the component is repeatedly bombarded the yield strength increases and so does both the reaction stress and the residual stress. This means that the dent diameter must progressively decrease – for a fixed peening intensity.

Because the sum of the reaction and residual stresses increases during peening so does the "hydrostatic component" of the stress system. The hydrostatic component of any three-dimensional stress system explains why rolling allows far greater extensions than does tensile stretching and why extrusion allows enormous plastic extension. For peening this hydrostatic component has a magnitude of – (q + r). Because it increases during shot peening it increasingly offsets the reduction in component ductility caused by work-hardening.

DISCUSSION

As stated previously, peening impressions (dents) are the "be all and end all" of shot peening. They govern not only coverage but also residual stress generation, surface work hardening, distortion/peening intensity, oxide removal and the roughening/smoothing of components. Dents themselves are, however, immediately apparent on a shot-peened component. Component properties that depend on dent characteristics have to be determined experimentally. Because of their primary importance dents deserve to be considered and specified more closely than is generally the case.

Upflow of material during impact generates annular ridges that have the potential to become harmful extrusion folds. The significance of the ridges depends upon the aspect ratio of the dent. A reduction of the aspect ratio of dents, whilst maintaining a required peening intensity, can be achieved by using a larger shot size.

The relationship given as equation (2) epitomizes dent creation. As peening progresses, factors such as yield strength, reaction stress and residual stress all increase. These combine to reduce the dent size and increase the ductility-enhancing hydrostatic effect. As a consequence, some features, such as coverage curves, must deviate from a simple two-parameter function. The deviation is predicted to be small but may be significant. This agrees with numerous practical observations.