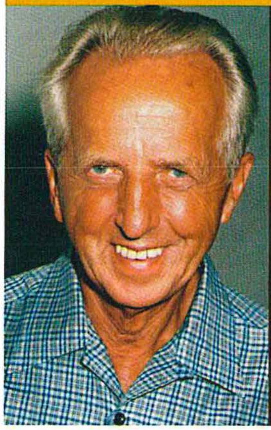

Effects of Indent Ratio on Curvature and Deformation of Sheet and Strip

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INTRODUCTION

Indent ratio in shot peening is the ratio of the indentation diameter, d, to the component thickness, T, see fig.1.

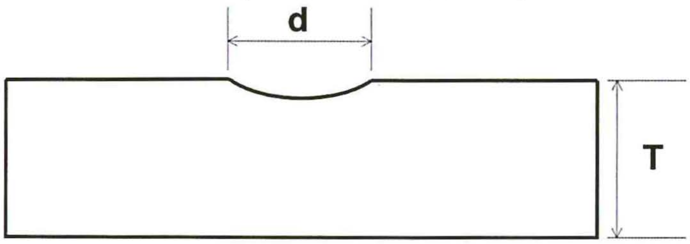

Fig.1 Indent ratio, d/T.

When the indent ratio is small, we get convex curvature of sheet and strip, for example with normal peening of Almen strips. Plastic deformation by the indentations is confined to a surface layer. When the indent ratio is large, we get concave curvature. Plastic deformation then occurs throughout the thickness of the material. At some intermediate indent ratio, the peened sheet or strip will have zero curvature.

Very simple experiments can be used to verify the behaviour described previously. Fig.2 shows an aluminium strip, 300 x 25 x 2mm, peened over a flat anvil using a peening hammer. Heavy blows were applied between B and C giving large indent ratios and hence inducing concave curvature. Deformation marks are present on the convex side of the region BC, showing that through deformation has occurred. Light blows applied between A and B, giving much smaller indent ratios, induced virtually zero curvature. No deformation marks are present on the lower surface of the region AB, indicating that through deformation has not occurred. Shot peening of identical strips using S170 shot, hence very small indent ratios, induced convex curvature.

Fig.2 Peening of 2mm thick aluminium strip using a peening hammer.

Quantitative relationships between indent ratio and curvature have yet to be established for a range of materials and peening media. Fig. 3 shows a speculative relationship based on existing information. Below a critical indent ratio, C.I.R., convex curvature is induced.

With indent ratios above C.I.R., concave curvature is induced. It is reasonable to assume that there must be a smooth

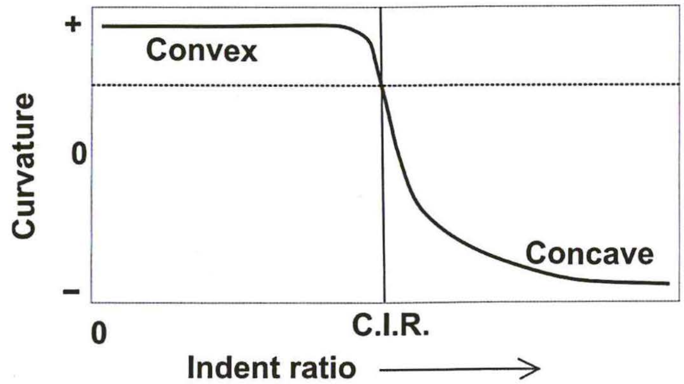

Fig. 3 Relationship between indent ratio and curvature induced on peening sheet or strip.

change on either side of the critical indent ratio. The magnitude of the curvature, for a given indent ratio, depends upon the peening intensity.

Two important areas of shot peening are affected by indent ratio. These are peen forming and Almen strip deflection. Peen forming can be carried out by using either small or large indent ratios depending upon application requirements. Almen strip deflection is a fundamental feature of peening control. If large indent ratios are applied to Almen strips then negative deflection (concavity) can be induced! One example is when Almen strips are peened using flat-ended needles. Currently there is a proposal to institute a thicker standard strip than the 'C' gage in order to accommodate intensity measurements involving very large diameter shot.

This paper examines why the indent ratio affects the type of curvature.

GENERAL SITUATION

With small indent ratios, tensile plastic deformation is confined to a surface layer – shown in fig. 4 as a net tensile deformation 'vector' (a 'vector' simply indicates direction and magnitude of a quantity). Because this net tensile deformation is above the neutral axis, we get convex bending.

Large indent ratios give tensile plastic deformation that occurs throughout the thickness of the sheet or strip. This through deformation increases with depth below the peened

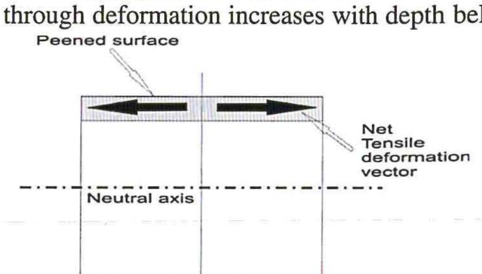

Fig. 4 Small indent ratio giving net tensile deformation vector above the neutral axis.

surface – as indicated in fig. 5. The variability of deformation is indicated by the varying length of the 'vector arrows'. Because the tensile deformation vectors are larger below the centreline than above it, we have a net tensile deformation vector that is below the neutral axis. That results in concave bending.

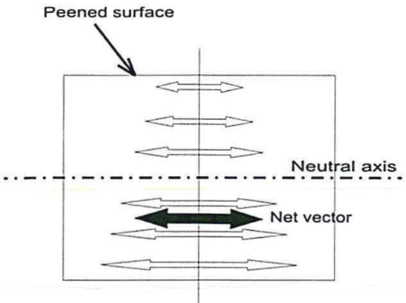

Fig. 5
Large indent ratio giving net tensile deformation vector below the neutral axis.

One important question is "Why does the tensile plastic deformation vary in the way shown in figs. 4 and 5?" In order to answer, or attempt to answer, that question we must apply indentation plasticity theory to the problem.

INDENTATION PLASTICITY THEORY

The force imparted by an impacting shot particle causes compressive stresses to be generated. When these stresses reach a critical value, the 'shear strength', plastic deformation by shear takes place. The maximum shear stress occurs at approximately 45° to the direction of the applied force. Fig. 6 shows a simplified representation of a single shot particle having produced an indentation of diameter d and a deformation region of width 2d and depth h in a thick block. The deformation region coincides with that part of the surface that has reached the shear strength for the material being peened. Outside the deformation region the applied stress is not high enough to cause plastic deformation and the material is elastically stressed.

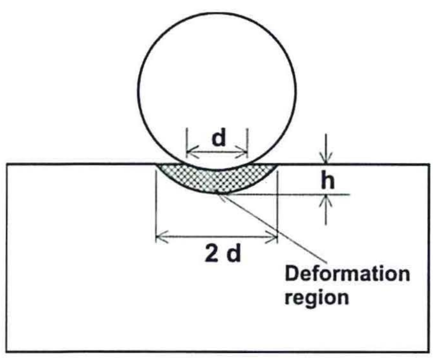

Fig. 6 Deformation region produced using small indent ratio.

A very useful part of plasticity theory involves what are termed "slip line fields". Slip line field theory evolved more than eighty years ago, with pioneering work being done by Prandtl. Today, we have numerous textbooks on the theory of plasticity – many containing several chapters devoted to applying slip line field theory to practical situations. Slip line field diagrams appear in several ICSP papers [1], [2]. Only the most basic aspects of the theory will be included here.

Essentially, we know that plastic deformation occurs by slip of crystal planes wherever the shear strength has been reached. The region of the component where the shear strength has been reached can be defined by a series of continuous lines that circumscribe a field (hence 'slip line field'). The rest of the component (where the shear strength has not been reached) is regarded as providing the support that is required for the 'field' to be generated.

Fig. 7 shows a 'text-book' slip line field appropriate to spherical indentation of a thick (semi-infinite) block. Under the action of the applied force, F, stresses equal to the shear strength of the material are present below the sphere. These shear stresses exist throughout the two regions ABCDE – which are the 'slip line fields'. Plastic deformation occurs within the two regions because the shear strength has been reached. The dashed line in fig. 7 indicates the original surface of the block and is where the indenting sphere first makes contact. On initial contact the applied force is zero – since force is stress multiplied by area of contact. As the indentation is being formed, both the area of contact and the force grow until they reach their maximum values. Thereafter, the sphere is rebounding and the force falls rapidly to zero.

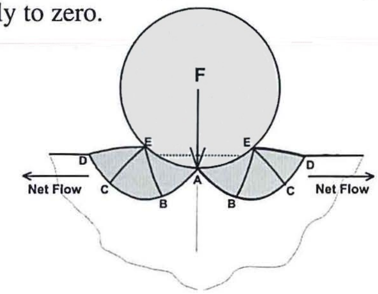

Fig. 7 Slip line fields for spherical indentation of a semi-infinite block of material equivalent to a small indent ratio.

It follows that the deformation zones (slip line fields) grow from zero area on initial impact to a maximum area when the shot particle is just on the point of rebound. Hence, the depth of plastic deformation is initially zero and grows to a maximum at maximum indentation depth. 'Net flow' is away from A and in both directions shown in fig. 7. The deformation region shown in fig. 6 can be regarded as the integral of progressive plastic deformation.

The absence of deformation just below point A in fig. 7 is related to the constraints imposed as material tries to flow either to the left or to the right. This flow encounters frictional restraint between the indenting sphere and the block along AE. Therefore, the downward pressure required for deformation reaches a maximum at A. The pressure distribution between A and E is equivalent to the 'friction hill' that is central to well-established rolling theory.

It is significant that predicted slip line fields depend primarily on the diameter of the indentation - rather than on depth of indentation. Hence, the depth of the deformed layer must also be primarily dependent on the indentation diameter. Real peened layers are, of course, the result of numerous indentations.

The term 'semi-infinite solid' has particular relevance to shot peening. A semi-infinite solid is limited in one direction – perpendicular and away from the surface – but has an infinite thickness. No real component can be a true 'semi-infinite' solid. It can often be so thick, however, that actual thickness has no significant effect on the plastic deformation zone. This occurs with small indent ratios when the thickness is many times the diameter of the indentation.

When indent ratios are high, the component cannot provide the support necessary for the type of slip line field shown in fig. 7. The slip line field now depends upon the indent ratio. Unfortunately, there are no published diagrams (to the author's knowledge) that describe the effect of indent ratio for spherical indenters. Diagrams do exist, in profusion, for flat indenters. Fig. 8 shows a speculative slip line field diagram for spherical indentation of thin strip.

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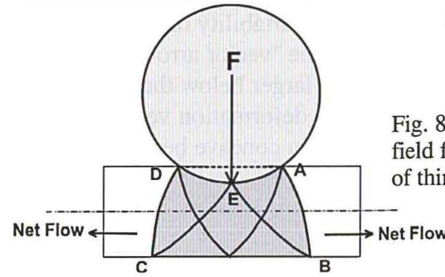

Fig. 8 Speculative slip line field for spherical indentation of thin strip.

Under the action of a force, F, the slip line field extends throughout the thickness of the strip. That means that plastic deformation is no longer confined to a surface region, but occurs throughout the section. The field has a greater area below the neutral axis than above it. This indicates that there will be a net flow outward below the neutral axis – leading to concave distortion of the strip.

There is another very significant difference between the types of deformation predicted by the slip line fields shown as figs. 7 and 8. With fig. 7, we have 'perturbation' of the surface around the indenter to produce the ridge surfaces DE. For the much larger indent ratios covered by fig. 8, there is no prediction of flow upwards adjacent to the edges of the indenter.

DISCUSSION AND CONCLUSIONS

Peen forming can be carried out by using either large or small indent ratios. The magnitude of the curvature induced will be proportional to the total amount of work done by peening. A minor proportion of the curvature is temporary, since that relates to the residual stress distribution in the curved component, and can be removed by stress-relief annealing. The major proportion of the curvature is permanent, as it relates directly to the non-uniform plastic deformation.

The net plastic deformation involved with large indent ratios is much greater than it is with small ratios. Greater curvatures can therefore be induced. Large indent ratios require, however, that the indentation diameters are relatively large. The corresponding unevenness of the surface may be a disadvantage.

Peening of Almen strips is a type of peen forming. It follows that very high Almen intensities cannot be accurately detected if it involves large indent ratios. That is why there has to be a range of Almen strip thicknesses – currently N, A and C. Even the thickest C strips would be inappropriate for large indent ratios. For a given shot size, type and velocity the indent ratio is reduced as the strip thickness increases. Hence, an even thicker gage of strip than C would be needed for very high Almen intensities.

Indent ratio also affects the 'ridges' that normally surround peening indentations. Above the critical aspect ratio, ridges disappear - which confirms the slip line field prediction given in fig. 8.

It should be noted that 'Slip line theory' is a convoluted area of indentation theory. It is virtually impossible to produce accurate field diagrams because of their dependence on imprecise variables such as work hardening, friction between sphere and surface, velocity effect and proportion of impact energy converted into heat. Nevertheless, the theory does give useful explanations of observed indentation phenomena.

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