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Optimum Peening Intensities

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Introduction

Shot peening improves fatigue resistance mainly by introducing self stresses (residual stresses). The compressive self stresses near the surface are balanced by tensile self stresses which decrease fatigue strength in the interior where stresses are usually lower.

The magnitude and distribution of the peening stresses depend mainly on the materials, not on the intensity. The intensity (specified in Almen numbers) determines the depth to which the compressive stresses extend below the peened surface. A low peening intensity will not increase the fatigue resistance as much as a higher intensity. Very high peening intensities may not increase the fatigue resistance as much as a lower intensity, partly because the tensile stresses at the interior become too high and partly because the compressive stresses become less for great depth of peening than for shallow peening. The optimum intensity is defined by the depth at which both decreased intensity and increased intensity would decrease the fatigue resistance. Figure 1 gives an example of optimum depth, based on assumptions explained in the discussion.

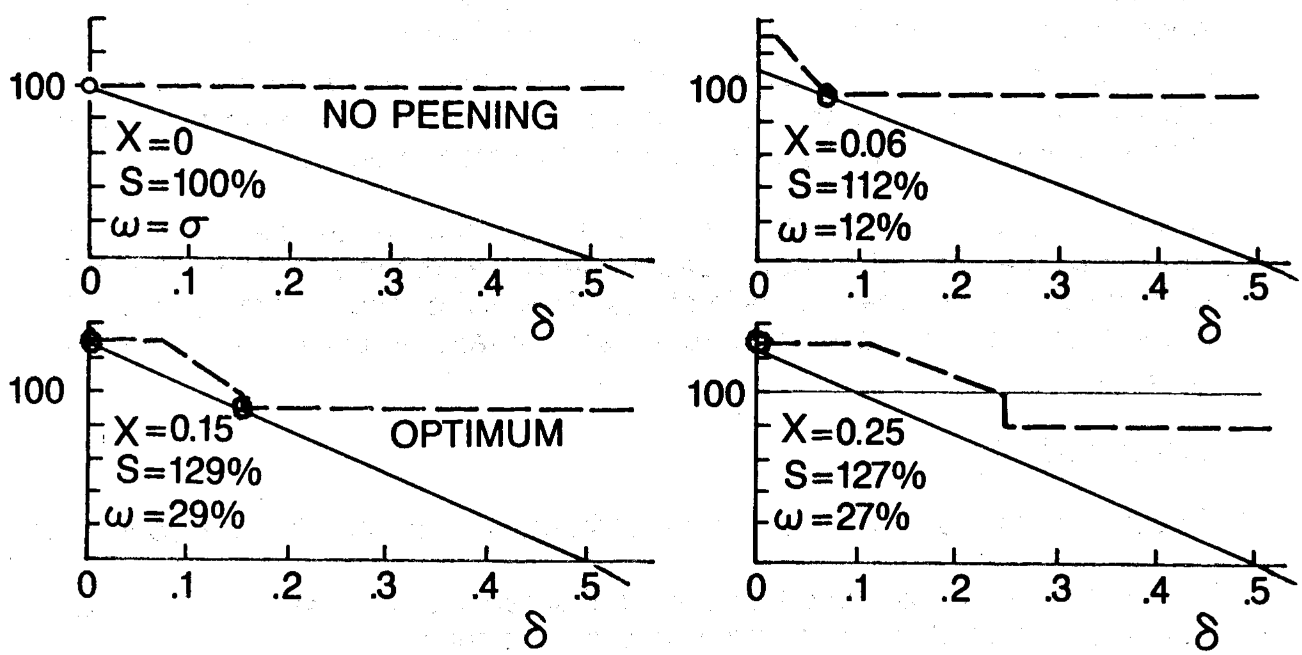
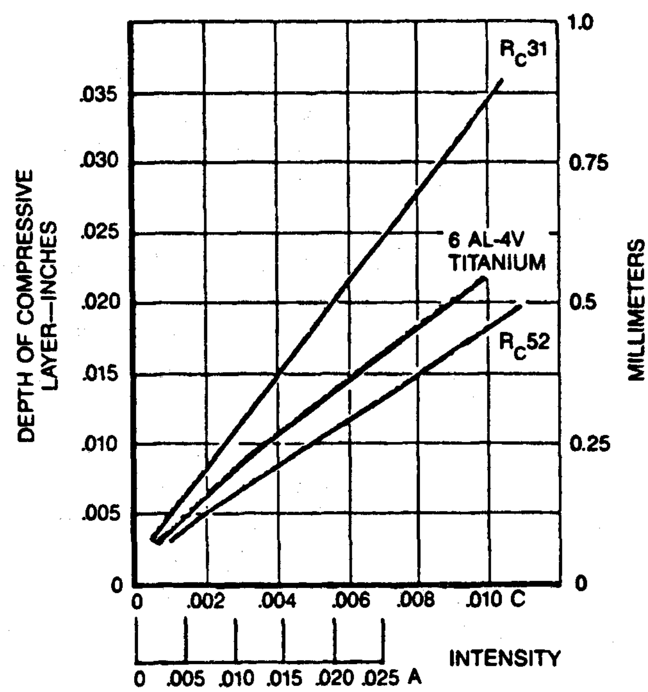


Fig. 1: Stress distribution and fatigue resistance for different depths of peening. Dashed line is the fatigue strength profile. Circles indicate origins of cracks. $\alpha\beta = 0.3$.

This optimum defined above is usually not the economic optimum because a somewhat lower intensity may not make much difference in the fatigue strength and may cost much less. We will show how to estimate the optimum depth of compressive stresses. The depth can then be converted to Almen intensity by using data from Brodrick [1] and others shown in Figure 2.

Fig. 2
Correlation of Almen intensity and depth of compressive stress



The self stresses change fatigue resistance by two entirely different mechanisms: The stress which can by endured without appearance of small cracks is increased by a fraction α of the compressive mean stress and decreased by a fraction of the tensile mean stress. This mechanism explains the effects of peening on many smooth or mildly notched parts.

Sharply notched parts, like threaded bolts, can endure stresses which start small cracks at the notch root because these cracks are arrested below the surface by the absence of tensile stress. This is the mechanism by which shot peening obtains spectacular improvements of fatigue resistance on notched parts

Required Data

To estimate an optimum intensity by computation one needs the following data:

Knowledge of the expected loads is the first requirement. We assume that they can be approximated by constant amplitude loading.

The distribution of load stresses in the part must be known. For smooth straight parts it is substantially linear. For symmetrical notched parts the stress profile below the notch can be approximated as

$$L = S[a + b(1-2x) + c(1-2x)^n] \qquad \text{Equ. 1}$$

where S is the nominal stress at the surface; x is the ratio of depth below the surface to the thickness of the part, a,b,c, and n are constants chosen so that the profile is in equilibrium with the nominal stress distribution, matches the stress concentration at the surface, and matches the stress gradient near the surface, as shown by Fuchs and Lee [2].

The distribution of peening stress can be approximated as

$$P = Q[1 - (1.33x/\delta - 0.33)^2] \text{ for } x<\delta \text{ and } Q = Q_0[1 - \delta^2/(1-\delta)^2]$$

where Q_0 is the maximum peening stress obtained on a very thick test piece, and δ is the ratio of depth of compressive stress to thickness. (This formulation does not consider the change in stresses which results from bending of a strip or leaf spring peened on one side only.)

In addition to these stress distributions one must know the product $\alpha\beta$ of two ratios which depend on the material
$\alpha = dF/dM$
where F is the fatigue strength and M the mean stress
and
$\beta = Q_0/F$. Both these ratios are negative. Their product is positive.

To check on changes of self stress by yielding one also needs to know the yield strength Y or the ratio Y/F. (Using ratios avoids the need to convert units and permits easy scaling to different sizes.)

Estimation of optimum depth of peening stress for a smooth part.

Figure 3 shows the calculated percentage increase ω of fatigue resistance of a smooth part, tested in bending from zero to maximum (R=0), peened on both sides, as a function of the relative depth δ for several values of the product $\alpha\beta$.

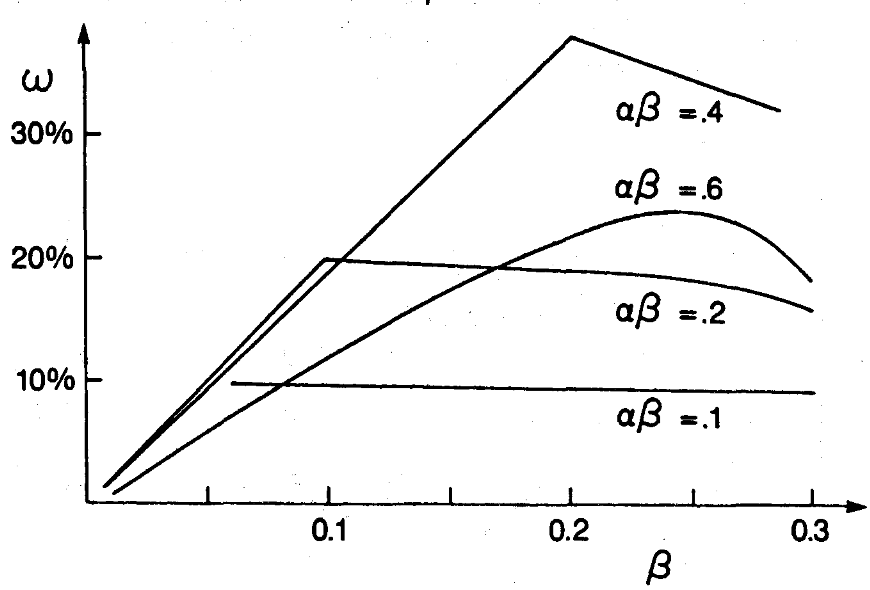


Fig. 3: Increase of fatigue resistance as a function of relative depth of compressive stress for several values of the product $\alpha\beta$

$\omega = \{1 - 1.44[\alpha\beta\delta\gamma(1-2\delta)]\}/(1-2\delta) - 1 \quad \gamma = 1 - \delta^2/(1-\delta)^2$ or Equ. 3a

$\omega = \alpha\beta\gamma$ whichever is less. Equ. 3b

The increase is almost linear with the depth up to $\omega = \alpha\beta$ where the expectation of failure at the surface is equal to that at depth δ. Then the increase drops off slightly, in proportion to the decrease in maximum peening stress with increase in depth of peening. For $\alpha\beta > 0.5$ the behavior changes.

Cracks are expected to start at the surface when the intensity is greater than optimum as indicated in Fig.1. The calculations assumed that for these specimens such cracks would not be stopped below the surface.

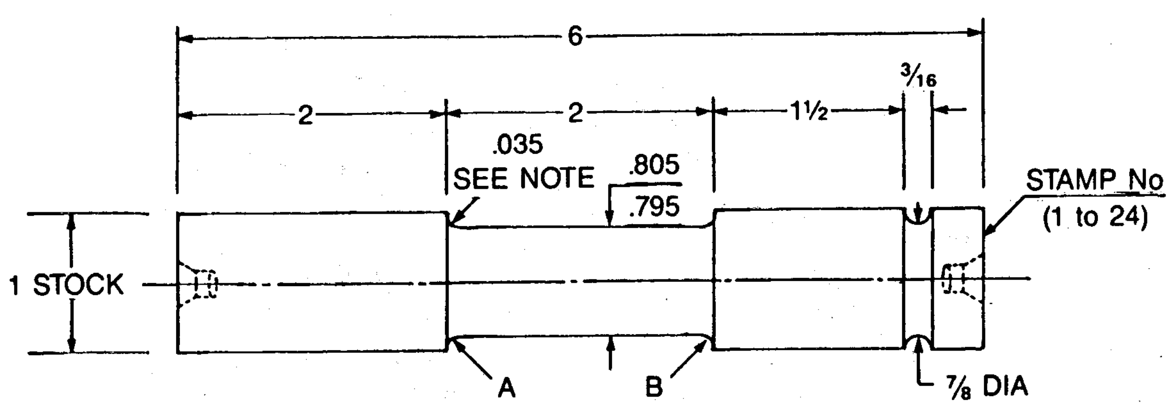
The optimum depth is o.5$\alpha\beta$ and the maximum expected strength increase is $\alpha\beta$ for the conditions assumed above, as long as $\alpha\beta$ is less than o.4.

The calculations assumed that the surface of the unpeened specimen is perfect and of strength equal to the interior. In practice the unpeened surface will be less strong so that light peening will produce larger increases of fatigue resistance than the calculated values.

This example is shown here because it demonstrates the important principles most clearly. The dependence of optimum peening depth and of the obtainable strength increase on the product of the two ratios α and β is the main conclusion. The next example is of great practical importance.

Optimum intensity for a notched part.

Figure 4 shows a specimen of 4340 steel, hardness Rockwell C52. The optimum intensity for rotating bending was calculated to be 9C. The conventionally specified intensity for this part is 7A, which is less than 1/4 of 9C. Rotating bending tests with 16 specimens showed a clear superiority of the heavily peened specimens. Their fatigue strength at 200000 cycles was more than 12% greater than the strength of the conventionally peened specimens.



DIMENSIONS IN INCHES
Fig. 4: Notched fatigue specimen for rotating bending tests.

The computation used the stress profiles of equations 1 and 2. For the load stress the constants were a = 0, b = 0.9, c = 1.1, n =30.2. The materials constants were α = -0.35, β = -1.6. For an assumed bending load we checked the conditions for crack initiation and for crack arrest at a series of points below the surface. If cracks initiated below the depth at which they were arrested the bending load was decreased for the next set of calculations. We searched for the highest bending load at which cracks were arrested below the surface and no other cracks were initiated below that point. This bending load was called the strength of the part. The calculations were then repeated for other peening intensities. The intensity for which the highest strength was calculated was the optimum intensity [3].

The profiles of stresses for one combination of bending moment and intensity are shown in Figure 5. We assumed that cracks will be arrested where the net stress, the sum of load stress and peening stress, is negative (compressive). Cracks start at point A but are arrested in the region of negative net stress. At a somewhat higher load cracks would also start at point B and propagate inwards.

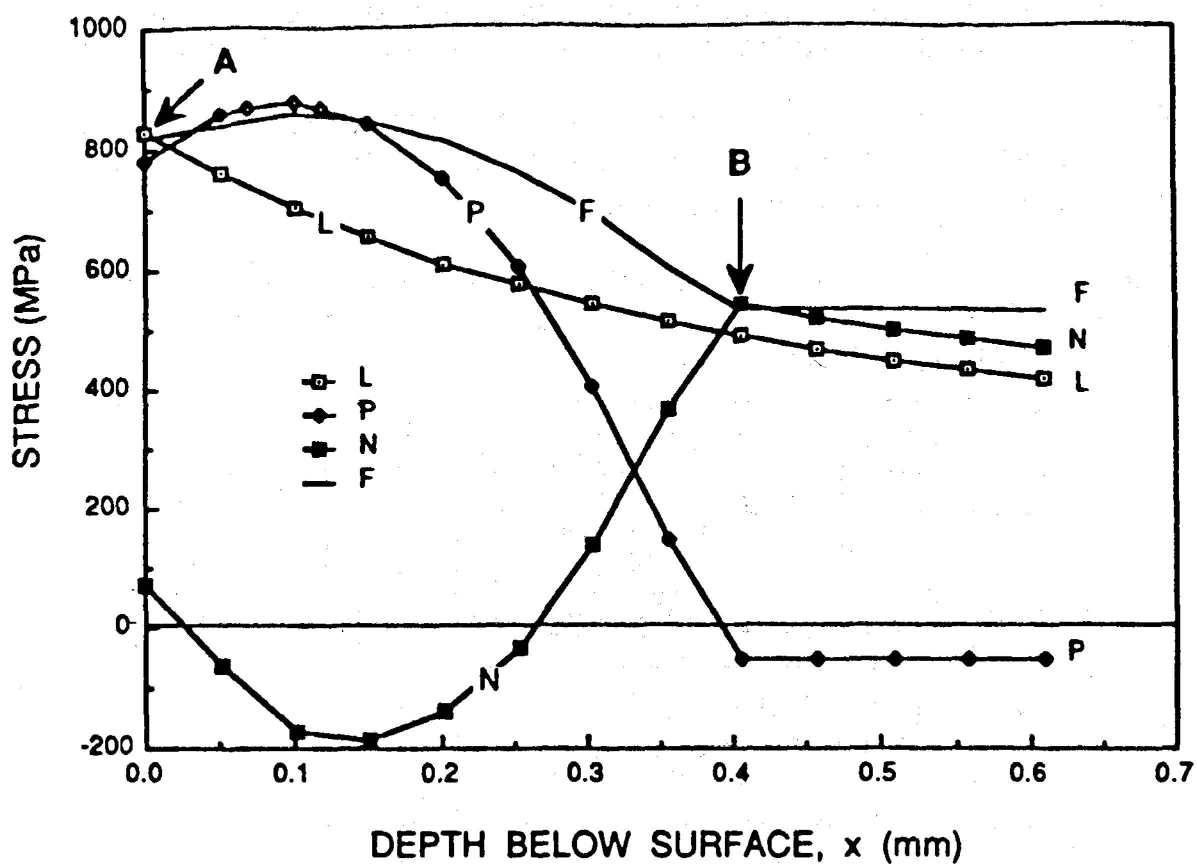


Fig. 5: Stress profiles below the notch of Fig.4.
L=load stress P = (peening stress)*(-1) N = net stress = L- P
F = fatigue strength = 552 + 0.35P (MPa)

In fully reversed loading (R=-1), such as rotating bending, the sum of peening stress and compressive load stress can exceed the yield strength. The remaining self stress is less than the original peening stress. This effect was included in the computations.

Discussion

To optimize shot peening one must consider the distribution of stresses and of strength below the surfaces of parts.

Figure 1 and equations 3a and 3b represent a very simple case. They are based on a number of assumptions which were made to keep the computation and results as transparent as possible.

The profile of peening stresses is shown by straight lines rather than by the parabola of equation 2. The formula, equation 3, also neglects the difference between surface self stress and maximum self stress. The factor 1.44, however, is based on the parabolic distribution.

The self stress depends partly on the depth of the plastic deformation. Peening on both sides so heavily that the plastic deformation extends to the center of the part will produce very little self stress. We do not know enough about the strains produced by peening to calculate the resultant stress distribution. We have assumed that the stresses decrease according to the factor γ of equation 3. They would approach zero as the depth of compressive self stress approaches the center, but decrease less than linearly for shallow depth of peening.

For the smooth part, Fig.1 and Fig.3, we assumed that cracks which start at the surface will not be arrested below the surface. Whether this is true depends on the ratio β and on the stress gradients.

This model is greatly simplified but the surprising characteristic shape of the curves in Figure 3 agrees with the results of the classic investigation by Mattson and Coleman [7] shown in Figure 6.

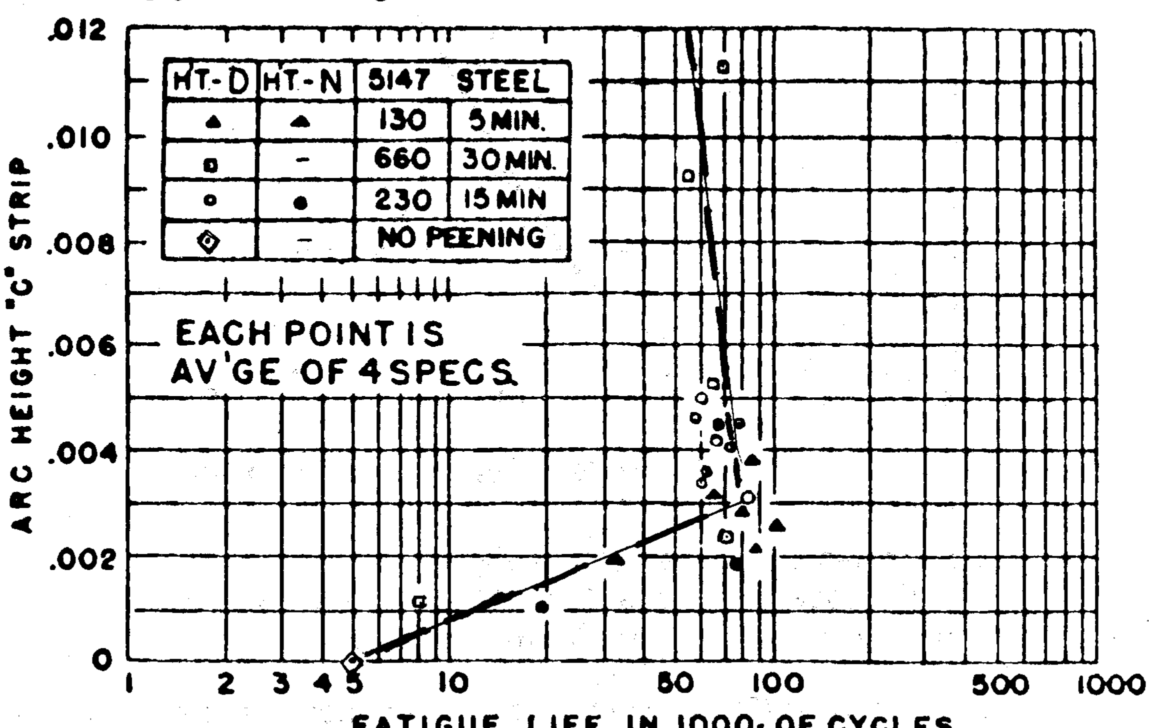


Figure 6. Effect of peening intensity on fatigue life [7]
(dashed line added by H.O.F.)

For the notched part, Fig.4, crack arrest below the surface is the key to the fatigue resistance. The fatigue strength F and the ratio α were taken from published constant life curves [4]. They should be taken for the expected fatigue life and for the applicable R-ratio. If constant life curves are not available one must use approximations such as the relation recommended by Morrow [5] which is usually better than the relations recommended by Goodman or by Gerber. A discriminating investigation by Baghdasarian [6] has shown that the Morrow relation overestimated the effect of mean stress for a low carbon steel and underestimated it for a high strength steel by substantial amounts.

The notched part tested in rotating bending will experience yielding of some of the self stress near the root of the notch. For the smooth part there will be no yielding near the surface where the load stresses are always tensile. For such a part, like a leaf spring, one would peen only one side. The bending produced by peening one side, as on an Almen strip, will change the stress distribution. We assumed peening on both sides to avoid the added term in the equation. For the same relative depth of peening the equilibrating tensile stresses will of course be higher for the round part of the second example than for the strip because the core area will be smaller.

The assumption that cracks will be arrested where the sum of load stress and self stress is zero or less corresponds to a threshold stress intensity range of zero. The actual threshold range is usually somewhat above zero, so that our assumption is conservative.

In early exploratory tests, reported in reference[3], six of the notched specimens were peened to 9C in one fillet and to 7A in the other fillet. All six broke in the lightly peened fillet. The life was about 50,000 cycles. In later tests for strength at about 200,000 cycles, with fillets peened to 9C or 11C, the two specimens broke after long life not in the fillets but in the one-inch diameter end section. The remaining two specimens, peened to 9C or 7C, broke in the 7C fillet. The strength at 9C is greater.

Conclusion

Great benefits can be obtained by shot peening, and even greater benefits if peening specifications are based on more careful analysis of the distributions of load stresses and of self stresses below the surface of parts.

References

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