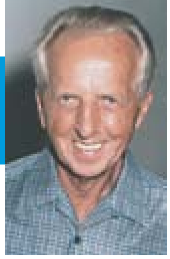

ACADEMIC STUDY
by Prof. Dr. David Kirk | Coventry University, U.K.

Estimate Compressed Layer Depth by Using Almen Peening Intensity

INTRODUCTION

Shot peening induces a surface layer that contains compressive residual stress. It is this compressed surface layer that is largely responsible for improved fatigue performance of components. The depth of the layer is therefore of pivotal importance to users. X-ray stress analysis, involving multiple layer removals, is the most accurate method of determining the depth of the compressed layer. Indirect methods, such as micro hardness profiles, also involve multiple layer removals. Both methods are tedious and expensive and are carried out after peening.

Almen peening intensity is necessarily available for every peening operation. This article describes how Almen peening intensity can be used as an acceptable guide to the depth of the compressed surface layer.

Most shot-peened components go directly into service. Occasionally, components are fine-finished after peening. This is done either to change the smoothness of the surface or to induce minor dimensional changes. Fine-finishing processes include polishing, lapping, honing and sanding. AMS 2432B provides some guidance as to the amount of material that can be removed without severely affecting the property enhancement provided by shot peening.

This article describes the principles that lie behind the limitation of surface removal by fine-finishing. Essentially only a small fraction of the compressed surface layer should be removed. The thickness of the compressed surface layer is rarely measured, whereas the peening intensity is, of necessity, always available. AMS 2432B attempts to use peening intensity values as a guide to the amount of material that can be removed. To some extent the article is complementary to some sections of AMS 2342B.

DEPTH OF COMPRESSED LAYER

The depth of the compressed surface layer, **D**, is of primary importance with respect to fine finishing – it controls the amount of material that can safely be removed. A typical residual stress profile is shown as fig.1. **D** varies with both peening intensity and hardness of the component material. 10% of the depth, **D**, would seem to be a reasonable maximum amount that could be removed without any significant adverse effects on service performance.

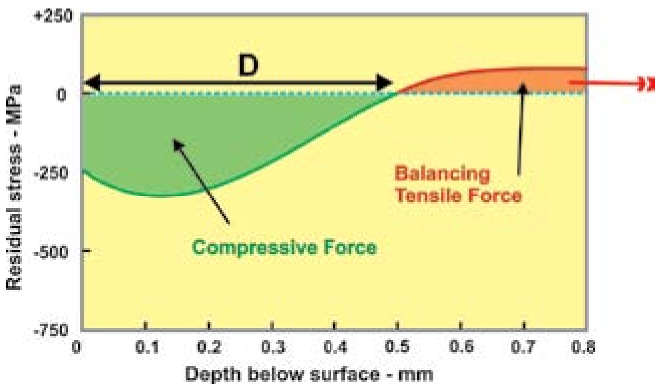

*Fig.1. Typical shot peening residual stress profile having a compressed layer depth, **D**.*

RELATIONSHIP BETWEEN DEPTH OF COMPRESSIVE STRESS AND ALMEN 'A' PEENING INTENSITY

It is reasonably obvious that the depth of the compressed surface layer will increase with increase of peening intensity. Also obvious is that the depth will be greater for soft materials than it will be for hard materials – for a constant peening intensity. Table 1, which uses some of the values in Table 2 of AMS 2342B, quantifies the effect of material strength.

In Table 1, a fixed Almen 'A' intensity, 0.20 mm, has been applied to a range of materials. For the values given, the average measured depth of 0.182 mm for **D** is certainly close

Table 1. Depths of Compressive Stress, D, for peening intensity of 0.20mm using 'A' strips

STRIP TYPE	A
Intensity - mm	**0.20**
Material	**D - mm**
Aluminum	0.25
Titanium	0.18
Steel < 1379 MPa	0.20
Steel 1379 MPa	0.13
Nickel Alloys	0.15
Average	**0.183**

to the applied peening intensity of 0.20mm Almen 'A'. This gives us the very useful relationship that:

The depth of compressive stress is, on average, approximately equal to the Almen 'A' peening intensity.

The values given in Table 1 refer to a specific peening intensity – 0.20 mm A. It is, however, reasonable to suppose that the depth, **D**, will be linearly proportional to peening intensity over the range of allowed range of peening intensities. This effect is illustrated by fig.2 – for which the 0.20 mm 'A' values have been extrapolated.

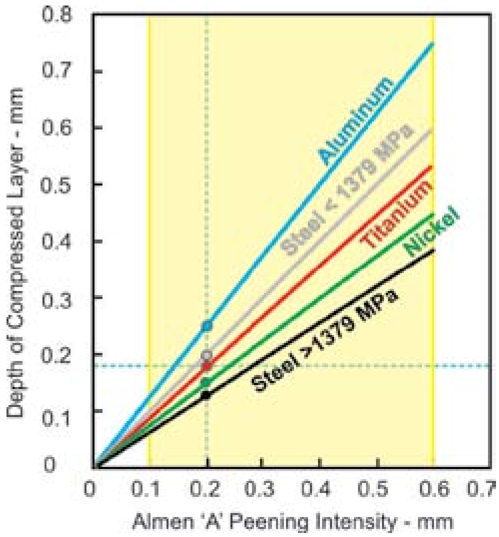

Fig.2. Projected variation of compressed layer depth with Almen 'A' peening intensity.

A second important observation is that:

The range of compressed layer depths (in Table 1) is in a ratio of less than 2 to 1.

To many shot peeners it might appear surprising that the range of depths is so small – given the large range of corresponding material strengths. It has, however, been shown (TSP 2004) that the diameter of a peening indent is inversely proportional to the fourth power of the material's Brinell hardness. A range of 2 to 1 of indent diameters would therefore need the hardness to vary by a factor of 16 ($2^4 = 16$). Compressed layer depths are directly proportional to indent diameters and Brinell hardness ratios are very similar to tensile strength ratios. For the materials given in the table the range of tensile strengths is about 17 to 1 – which is very close to 16 to 1. Extending that argument, a range of 3 to 1 of compressed layer depths would require the tensile strengths to vary by a factor of 81 to 1 (81 being 3^4) which covers the full range of tensile strengths for available shot-peened materials.

Fig.3 illustrates the relationship between indent diameter and compressed layer depth. For a soft material, **A**, the indent diameter, $\mathbf{d_A}$, and the compressed layer depth, $\mathbf{D_A}$, are both less than those for a hard material, **B**, - $\mathbf{d_B}$ and $\mathbf{D_B}$.

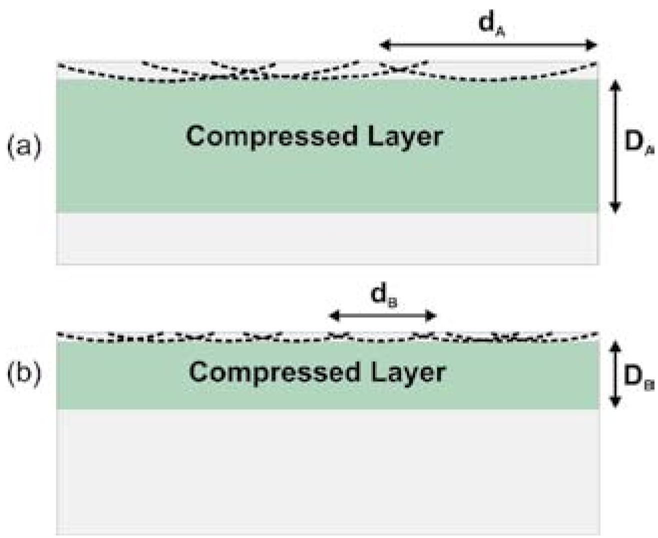

Fig.3. Doubling indent diameter doubles compressed layer depth, ***D****.*

Fig.2 indicates that for the compressed layer depth, D, that:

(1) D is approximately equal to the Almen 'A' peening intensity for materials of average tensile strength,

(2) For very soft materials, such as aluminum, D can be as much as 50% more than the Almen 'A' peening intensity and

(3) For very hard materials, such as high-strength steels, D can be as little as half of the Almen 'A' peening intensity.

Going from peening intensity plus 50% down to half of peening intensity is a range of 3 to 1. That, as mentioned earlier, corresponds to a range of 81 to 1 in tensile strengths of component materials.

RELATIONSHIP BETWEEN DEPTH OF COMPRESSIVE STRESS AND TYPE OF ALMEN PEENING INTENSITY

Almen 'N' and Almen 'C' strips are also used to measure peening intensity–though not as often as are Almen 'A' strips. Table 2 (page 34) uses all of the values published in Table 2 of the AMS 2432B Specification. Almen 'N', 'A' and 'C', intensities of 0.20 mm have been applied to a range of materials and corresponding depths of compressive stress are presented.

The ratios of 3.14 (for A/N) and 2.95 (for C/A) are close to the 'conversion factors' specified in J442. Those are that "C strip reading x 3.5 = A strip reading and A strip reading x 3.0 = N strip reading". Hence, as guiding principles, it can be postulated that:

(1) D is approximately equal to one-third of the Almen 'N' peening intensity for materials of average tensile strength and

(2) D is approximately equal to three times the Almen 'C' peening intensity for materials of average tensile strength.

It has already been shown that: (a) for very soft materials, such as aluminum, **D** can be as much as 50% more than the Almen 'A' peening intensity and (b) for very hard materials, such as high-strength steels, **D** can be as little as half of the Almen 'A' peening intensity. Extending this to 'N' and 'C' strips allows the construction of the graphs shown as figs.4 to 6.

An approximate compressed layer depth can be read off from the appropriate figure using a measured value of Almen peening intensity. For example: in fig.4 a measured Almen peening intensity of 0.5 mm 'N' indicates that the compressed layer depth will be between 0.08 mm and 0.25 mm – depending on component hardness. If the component is known to be of average hardness the depth would be indicated as being 0.15 mm.

PERMITTED LAYER REMOVAL BY FINE FINISHING

A 10% removal of the compressed layer depth would appear to be a reasonable maximum. There are, however, some specifications that provide definite limits – notably AMS 2432B. This allows for the fact that the actual depth of the compressed layer is not usually measured. Instead it relies on the readily available Almen peening intensity values – as stated earlier. A further restriction requires that "… evidence of peening impressions shall remain after material removal."

Specified Amount of Layer Removal

AMS 2432B states: "For parts with a specified minimum tensile strength of 220 ksi (1517 MPa) and over, no more than the equivalent of 5% of the specified minimum "A" intensity …shall be removed from the surface". Hence it would follow that if the specified range was 0.20-0.30mm Almen 'A' then 5% of 0.20 mm would be the maximum that could be removed from components for which the tensile strength was at least 220 ksi (1517 MPa). 5% of 0.20 mm is 0.01 mm. Using fig.5 indicates that the compressed layer depth for very hard materials is about 0.10mm. Removal of 0.01 mm from a layer depth of 0.10 mm corresponds to removing 10% of the layer's thickness.

AMS 2432B also states: "For other parts, no more than the equivalent of 10% of the specified minimum "A" intensity … shall be removed from the surfaces". If the specified range was 0.20 - 0.30mm Almen 'A', then 10% of 0.20 mm would be the maximum that could be removed from components for which the tensile strength was less than 220 ksi (1517 MPa). 10% of 0.20 mm is 0.02 mm. Using fig.5, a compressed layer depth of 0.20 mm appears for materials of average tensile strength. Hence for components of average tensile strength 0.02 mm could be removed, which corresponds, again, to 10% of the compressed layer thickness.

AMS 2432B accommodates the fact that intensity may have been specified using either 'N' or 'C' scales. It does this

Table 2. Depths of Compressive Stress (AMS 2432B values)

STRIP TYPE	N	A	C
Intensity-mm	0.20	0.20	0.20
Material	Depth of Compressive Stress - mm		
Aluminum	0.08	0.25	0.69
Titanium	0.05	0.18	0.46
Steel < 1379 MPa	0.06	0.20	0.64
Steel > 1379 MPa	0.05	0.13	0.38
Nickel alloys	0.05	0.15	0.51
Averages	**0.058**	**0.182**	**0.536**

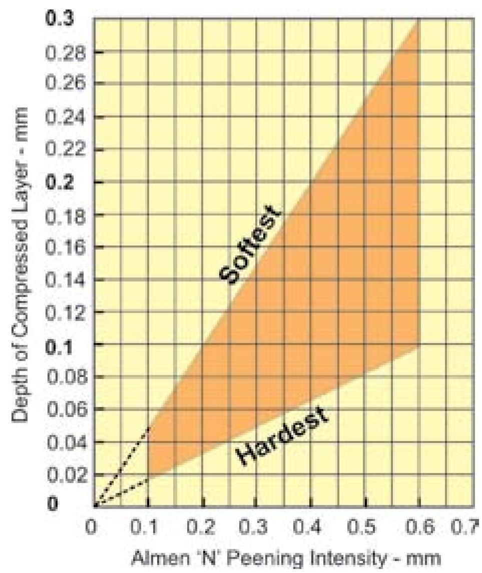

Fig.4. Guideline Diagram for Conversion of Almen 'N' intensity to Depth of Compressed Layer.

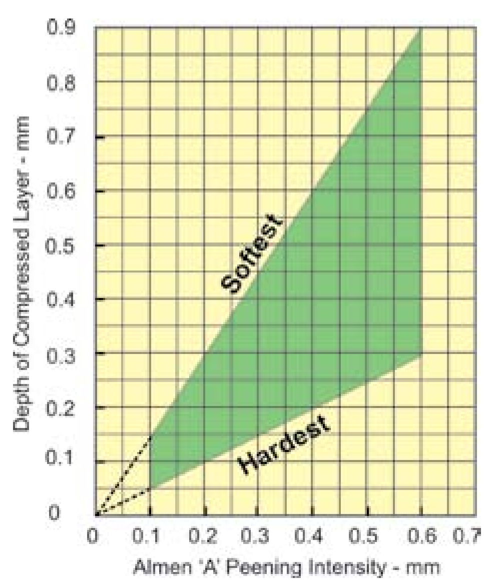

Fig.5. Guideline Diagram for Conversion of Almen 'A' intensity to Depth of Compressed Layer.

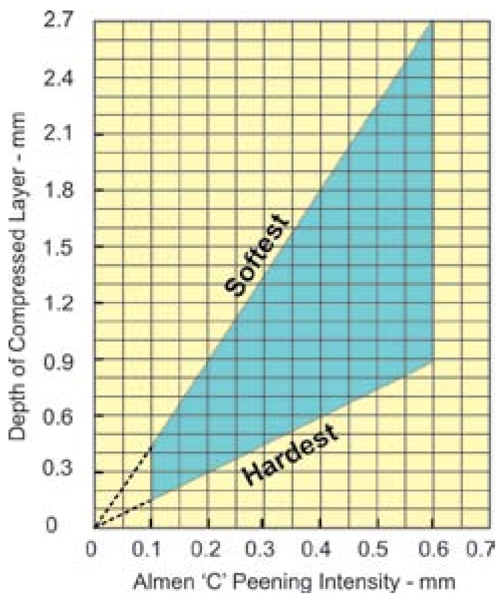

Fig.6. Guideline Diagram for Conversion of Almen 'C' intensity to Depth of Compressed Layer.

by using the phrase "… or equivalent "N" or "C" intensity (See 8.6)…" This applies for parts with a minimum tensile strength of 220 ksi (1517 MPa). Section 8.6, Intensity Comparisons, contains the familiar (a) "…Type "A" test specimen deflection may be multiplied by three to obtain the approximate deflection of any Almen test strip Type "N" specimen when shot peened with at the same intensity" and (b) Type C Almen test specimen deflection may be multiplied by 3.5 to obtain the approximate deflection of a Type A Almen test strip when shot peened with at the same intensity". Two examples are:

(1) A specified range of 0.35-0.50 mm Almen 'N' intensity for parts with a minimum tensile strength of 220 ksi (1517 MPa) means that first we must divide the minimum 0.35 mm by 3.5 (giving 0.10 mm) and then divide that by 20 (to give the 5% allowance). This yields 0.005 mm as the maximum that can be removed by fine finishing. Using fig.4 indicates that for an Almen intensity of 0.35 mm 'N' the compressed layer depth would be about 0.058 mm. Removing 0.005 mm from a depth of 0.058 mm is about 9%.

(2) A specified range of 0.30-0.45 mm Almen 'C' intensity means that we multiply the minimum 0.30 mm by three (to give 0.90 mm) and then divide by 20 (to get 5%) giving 0.045mm. Using fig.6 indicates that the compressed layer depth (for hardest material) would be about 0.45mm. Removing 0.045 mm from 0.45 mm is 10%.

Somewhat ambiguously, for "other parts" i.e. of lower tensile strength, AMS2432B refers to its section 8.3.4.2 for guidance on equivalence. That section is, in fact, simply the Table 2 mentioned earlier in this article. For practical reasons it is better to follow the 'equivalence' defined in the previous paragraph. The following two examples refer to "other materials" i.e. less than 220 ksi (1517 MPa).

(3) A specified range of 0.35-0.50 mm Almen 'N' intensity means that again we divide the minimum 0.35 mm by 3.5 to give 0.10 mm. This can now be divided by 10 (to give the 10% removal allowance. Hence we are allowed to remove 0.01 mm. Using fig.4 at 0.35 MM Almen 'N' the compressed depth is about 0.10 mm – for components of average tensile strength. That again corresponds to 10%.

(4) A specified range of 0.30-0.45 mm Almen 'C' intensity means that we multiply the minimum 0.30 mm by three (to give 0.90 mm) and then divide by 10 (to get 10%) giving 0.090mm. Using fig.6 indicates that the compressed layer depth (for material of average hardness) would be about 0.90 mm at 0.30 mm Almen 'C' intensity. Removing 0.090 mm from 0.45 mm is, yet again, 10%.

Evidence of Peening Impressions

AMS 2342B also requires that if fine finishing has been applied then "…evidence of peening impressions shall remain after material removal." It has been shown, in the previous section, that up to about 10% of the compressed layer thickness can be removed by fine finishing. Such an amount can only be removed if evidence of peening remains. This can only be achieved if the peened surface roughness exceeds 10% of the compressed layer depth, **D**.

Fig.7 is a schematic representation of a peened surface with a roughness just exceeding 10% of **D**. This shows a region of potential "evidence" of prior shot peening.

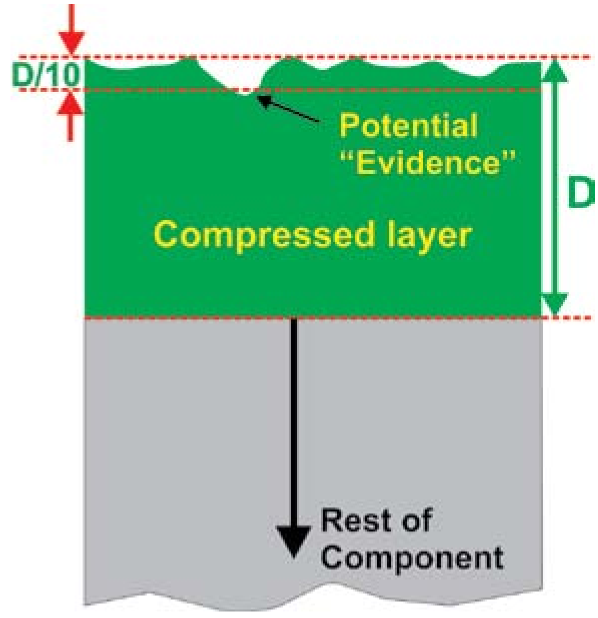

*Fig.7. Surface roughness just exceeding 10% of the compressed layer depth, **D**.*

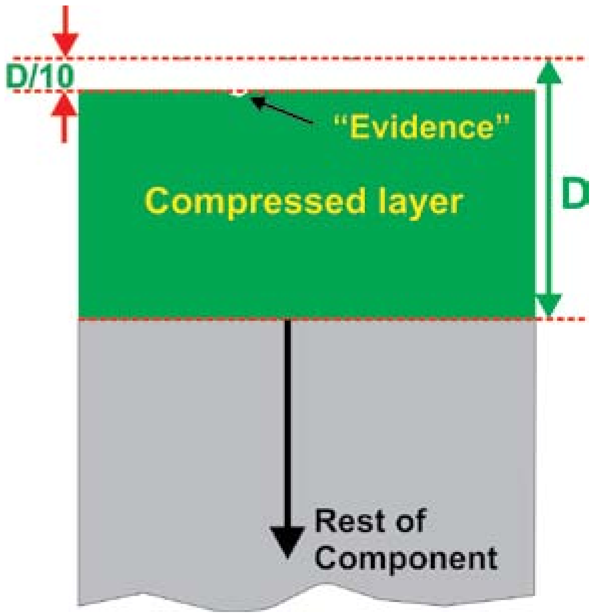

Fig.8. Fine-finished surface with 10% removal of compressed layer depth, ***D****.*

With 10% of the compressed layer depth, **D**, removed we have the situation represented in fig.8. The required "evidence" of shot peening is indicated in fig.8.

Normally, significantly less than 10% of the compressed layer depth would be removed by fine finishing. It is noteworthy that permitted material removal only involves 'slicing off the tops' of the roughness profile.

Compliance with the requirement to provide "evidence of prior peening" requires some expertise in identifying such "evidence". A simple way to obtain this expertise involves fine-finishing shot-peened Almen strips. Fig.9 shows an Almen 'A' strip that has been hand-polished in just a part of its convex surface - Blu Tack™ being used on the concave surface to provide grip. After just twenty strokes on medium-grade wet-and-dry emery paper the central region was completely devoid of any "evidence" of shot peening. Away from this region "evidence" progressively appears.

Fig.9. Hand-polished Almen 'A' strip showing area of complete indentation removal.

DISCUSSION

It has been shown that reasonable estimates of compressed layer depth can be obtained using the corresponding Almen peening intensity values. Such estimates would be of particular value in the planning stages of specifying a shot peening treatment for new components. It is important to realize, however, that final implementation should involve confirmation. This is classically available using x-ray diffraction techniques. They do require multiple layer removal and are, therefore, necessarily, expensive.

The analysis presented in this article relies entirely on the published values of layer depth versus Almen intensity presented in AMS 2432B. Further evidence can be acquired by comparing individual published values with the diagrams that have been presented.

Fine-finishing of shot-peened components is occasionally necessary. One question that has been asked is "How much of a shot peened surface can be removed without adversely affecting fatigue performance?" This article shows that, by following the AMS 2432B guidelines, less than 10% of the compressed layer depth will have been removed. Removal "slices off the tops" of the roughness 'hills'. These contain a relatively-low level of compressive residual stress. Fine finishing, of itself, introduces a high level of compressive residual stress. It follows that controlled fine finishing should not reduce fatigue strength and might even improve it.