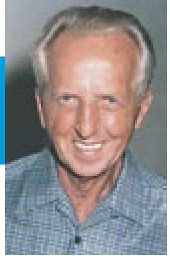

ACADEMIC STUDY

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Principles of Almen Strip Selection

INTRODUCTION

The guiding principles for Almen strip selection are thickness, variability and shape. Thickness selection, **N**, **A** or **C** is a normally matter for users rather than shot peeners.

Thickness is the most important factor, because it is directly connected to the users' peening intensity requirement. As a general rule, the greater the required peening intensity the thicker will be the most appropriate Almen strip.

Every Almen strip has some variability – in spite of having to meet specification requirements. The tighter the specification the greater will be the cost incurred in satisfying those requirements. It follows that critical components (for which shot peening generates a large added value) will justify the use of higher quality Almen strips than non-critical components.

Almen strips are normally rectangular and are available in both standard size and as 'mini-strips'. Circular 'strips' are also available for the continuous generation of peening intensity curves.

This article aims to show <u>why</u> proper selection of thickness, variability and shape of Almen strips are important factors in satisfactory shot peening. There are a very large number of 'in-house' specifications for Almen strips as well as the familiar SAE specifications J442 and J443. To avoid unnecessary complexity, the article is based on the SAE specifications.

THICKNESS

SAE J442 specifies three standard thicknesses of Almen strips – designated as **N**, **A** and **C**. The corresponding allowed thickness ranges are 0.76/0.81, 1.27/1.32 and 2.36/2.41 mm respectively. All three have the same major dimensional ranges of 75.6/76.6 mm length and 18.85/19.05 mm width. The approximate relationships between peening intensity arc heights are that:

C strip reading x 3.5 = **A** strip reading and

A strip reading x 3.0 = **N** strip reading.

SAE J443 recommends that **A** strips be used for peening intensities from 0.10 mm to 0.60 mm. For intensities below 0.10 mm **N** strips are recommended and **C** strips for intensities above 0.60 mm. These recommendations are simplistic because (a) they do not allow for overlapping specified intensity ranges, (b) no lower or upper limits for **N** strips are recommended and (c) no upper limit for **C** strips is recommended. The overall situation is summarized in fig.1. This indicates (1) that the sensitivity of **N** strips is 3 times that of **A** strips, (2) that the sensitivity of **A** strips is 3.5 times that of **C** strips (3) recommended limits for the use of **A** strips and (4) a lower limit zone from 0.10mm downwards where there is an increasing lack of measurement precision.

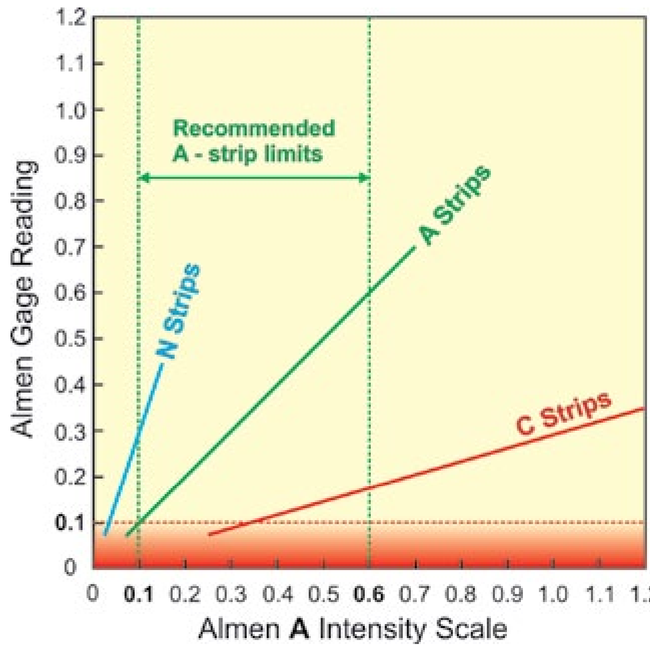

Fig.1 Almen strip sensitivities and recommended ranges of application.

The majority of shot peening is carried out with Almen **A** strips being involved. They are, however, the only ones that have specified upper and lower peening intensity limits. These recommended limits are illustrated in fig.1 and in fig.2.

An important question is:

Why are upper and lower limits recommended for Almen A strips?

Specified Lower Limit when using Almen A strips

A recommended lower limit of 0.10mm is specified because it has been judged

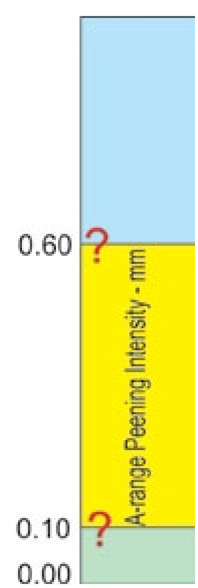

*Fig.2 Recommended Peening Intensity Limits for Almen **A** Strips.*

that any value below 0.10mm cannot be measured with sufficient precision. This is logical if we compare measurements less than 0.10mm with the specified Almen gage precision of 0.001mm. For example, a reading measurement of 0.050mm reflects an actual strip deflection anywhere between 0.0495mm and 0.0505mm – for which the instrument would have to round to 0.050mm. With this example there is a ± 1% inaccuracy range. If, for the same shot stream, the thinner **N** strip was being used then the gage would now read 0.150mm rather than 0.050mm (deflections being some three times greater). Instead of a ± 1% inaccuracy range we now have ± ⅓% accuracy.

Specified Upper Limit when using Almen A strips

The specified recommended upper limit when using **A** strips is an intensity of 0.60mm. This compares with the strips' thickness of 1.295mm. Hence the ratio of allowed peening intensity to strip thickness is approximately 0.5. This limiting ratio can, and probably should, be applied to the other thicknesses of Almen strips.

Shot peening produces a surface layer of plastically-deformed, compressively-stressed, material. The depth of this layer increases with peening intensity. Increased peening intensity is generated by using a combination of increased shot diameter and shot velocity. If the depth of the deformed layer becomes too high a proportion of the strip thickness then strip deflection decreases. For the extreme example of using flat-ended needles it has been found that strip deflection becomes negative! The theoretical reasons for this behavior have been given in previous articles in this series.

Fig.3 is a schematic representation of observed findings for **A** strips. There is a linear response in terms of measured peening intensity against 'true' peening intensity from A to B. This is the 'working range' for **A** strips. Beyond point B there is an increasingly-rapid deviation from linearity.

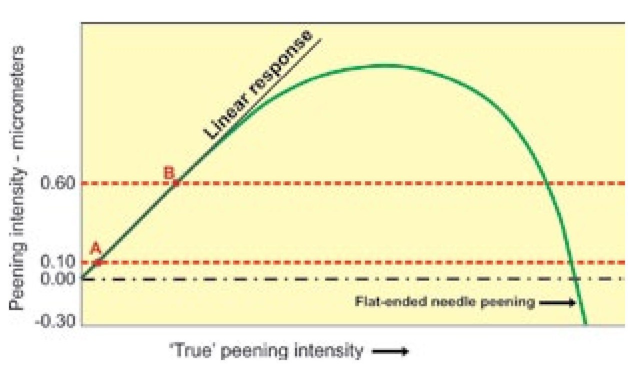

Fig.3 Schematic representation of measured peening intensity varying with 'true' peening intensity.

Upper and Lower Limits when using Almen N strips

It was pointed out previously that the recommended peening intensity upper limit for **A** strips was half of the strip thickness. Applying this ratio to **N** strips shows that the upper limit should be 0.39mm (0.785 x 0.5). The lower limit should be the same as for **A** strips – 0.10mm - applying the same argument about acceptable precision of measurement.

Upper and Lower Limits when using Almen C strips

Applying the 'half of strip thickness' concept to **C** strips would indicate that an upper limit of 1.20mm would be reasonable. The lower limit could be the same as for **N** and **A** strips – 0.10mm - applying the same argument about acceptable precision of measurement.

Specified Peening Intensity Ranges

Users specify an allowed range for their required peening intensity as well as specifying the thickness of strip that has to be used (**N**, **A** or **C**). Any specified range may, however, span over a 'recommended limit' e.g. 0.50 to 0.70mm using **A** strips. This is not a problem because it is recognized that measurements do not suddenly become invalid if they exceed a recommended limit. To allow a limited amount of overlapping is perfectly logical. Fig.1 includes a representation of reasonable amounts of overlapping - based on the previous arguments (gage precision and depth of deformed layer induced by peening). Users could use the mid-point of their required intensity range as a guide. For example the mid-point of a 0.50 to 0.70mm range when using **A** strips is 0.60. This does not exceed the recommended limit of 0.60mm, so that **A** strips should be specified. On the other hand a range of 0.08 to 1.10mm using **A** strips would have a mid-point of 0.95mm so that **N** strip usage should therefore be specified (with the three-fold correction) to become 0.24 to 0.33mm using **N** strips.

Effect of Strip Thickness on Gage Reading

Conventional Almen gage dials have a measuring tip that necessarily contacts the unpeened strip surface with some degree of force. This force is reported to vary between from about 50g up to 300g - depending on the manufacturer and the indicator mechanism involved. The force is a combination of an internal spring's force and the elastic resistance of any protective bellows surrounding the indicator's stem. Almen strips held on an Almen gage are therefore subjected to a tip force and must therefore bend – even if they have not been peened. Deflection of Almen strips under load has been the subject of detailed analysis in a previous article (TSP Fall 2009). The appropriate text-book, universally-recognized, bending of beams equation is that:

$$\mathbf{h = F^*s^3/(48^*E^*I)} \qquad (1)$$

where **h** = maximum deflection at the center of the beam, **F** = force applied to the center of the beam, **s** = distance between support points, **E** = Elastic modulus of the beam and **I** = Second moment of area of the beam (equal to $\mathbf{w^*t^3/12}$ for rectangular beams when **w** is width and **t** is the thickness).

Equation (1) assumes that the beam is supported on rollers whereas an Almen gage uses four support balls. Some additional transverse deflection is therefore generated. This additional deflection is one-eighth of the longitudinal deflection (assuming no anisotropy of elastic modulus). Equation (2) incorporates the additional transverse deflection.

$$\mathbf{h = 1.125*F*s^3/(48*E*I)} \qquad (2)$$

The units for the force, **F**, are Newtons (N). A mass of 1kg will normally exert a force of 9.81 Newtons (the 9.81 being the numerical value of the standard acceleration due to gravity). Hence a mass of 1g will exert a force of 9.81×10^{-3}N. Substituting $E = 200kNmm^{-2}$, s = 31.75mm and w = 18.95mm into equation (2) gives the following relationship between strip deflection, **h** (in mm), tip force, **T** (in grams) and strip thickness, **t** (in mm):

$$\mathbf{h}\text{(in mm)} = \mathbf{T*9.81*10^{-3} *31.75^{3}*12/(48*200*10^{3}*18.95*t^3} \qquad (3)$$

which simplifies to:

$$\mathbf{h}\text{(in mm)} = \mathbf{T*2.071*10^{-5}/t^3} \qquad (4)$$

Equation (4) can be used to plot the variation of strip deflection caused by a range of gage tip forces. This has been done in fig.4 where the average thicknesses of Almen strips have been substituted.

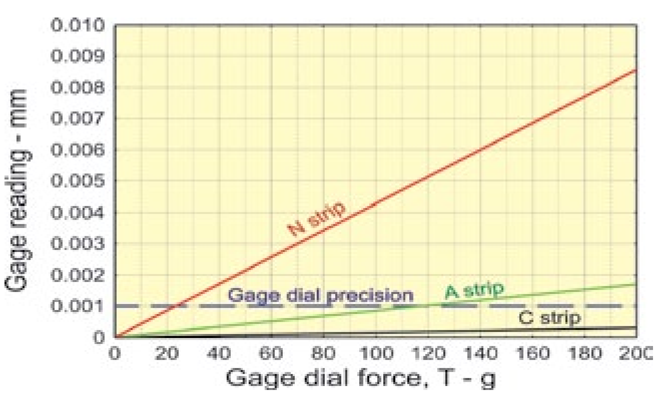

Fig.4 Effect of gage dial force on Almen strip deflection.

For a specified gage dial precision of 0.001mm (1 micrometer), strip deflection would not be detectable for **C** strips, barely detectable for **A** strips but would be expected for **N** strips. As an example consider a perfectly-flat unpeened Almen **N** strip being placed on an Almen gage whose dial exerted a tip force equivalent to 140g. Fig.4 predicts that the gage would read a positive deflection of 0.006mm. Turning the perfectly-flat strip over on the gage would again indicate a positive deflection of 0.006mm. This is equivalent to a "double phantom pre-bow"!

A simple experiment was carried out to examine the unsupported claim that "dial gages exert a force of up to 300g". Force meters are generally very sophisticated (and therefore expensive) but at least one simple but effective instrument is available for less than $20. Fig.5 illustrates that instrument together with a typical analogue dial gage. 'UHU White Tack' was used to secure the push/pull spring balance to a heavy block whilst the dial gage was clamped.

Fig.5. Push/pull spring balance testing resistance force of an analogue dial gage tip.

Fig.6 shows the same push/pull spring balance being applied to a standard EI Almen gage – placed in a horizontal position for ease of measurement. The arrangement allows the 'force meter' to be 'inched' towards the dial gage (or should that read "micrometered"!).

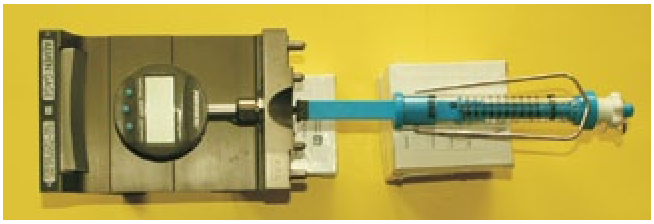

Fig.6. Push/pull spring balance testing resistance force of an EI TSP-3 Almen gage.

Table 1 shows some of the values obtained for dial gage tip resistance when testing the author's two analogue dials and two digital dial gages. General conclusions can be made – in spite of having tested only four dial gages. These are that (1) analogue gages impart a substantially larger tip resistance than do digital gages and (2) the tip resistance increases with

Table 1. Dial gage tip resistance forces

Gage	Initial Resistance - g	Resistance at 1.00 mm deflection - g
Analogue gage A	110	135
Analogue gage B (jeweled)	75	105
Digital gage - EI TSP-3	40	50
Digital gage - EI TSP-3 Aero	40	50

gage deflection. For the digital gages the tip force exerted on an Almen **N** strip would be predicted to induce a deflection of between 0.001 and 0.002mm (according to fig.4). For the analogue gages the corresponding deflection would be in the range 0.003 to 0.006mm.

VARIABILITY OF ALMEN STRIPS

Almen strip variability is only one of the several factors that shot peeners have to cope with. Others include shot size, shot shape, velocity, stand-off distance, impact angle, component shape and hardness. Collectively these variables mean that saturation curves must have a corresponding variability. This is illustrated by the 'reference example' shown in fig.7. For this example it is assumed that the mean peening intensity for a number of saturation curves, produced using a given quality of Almen strips and fixed peening conditions, was found to be 10 (imperial units).

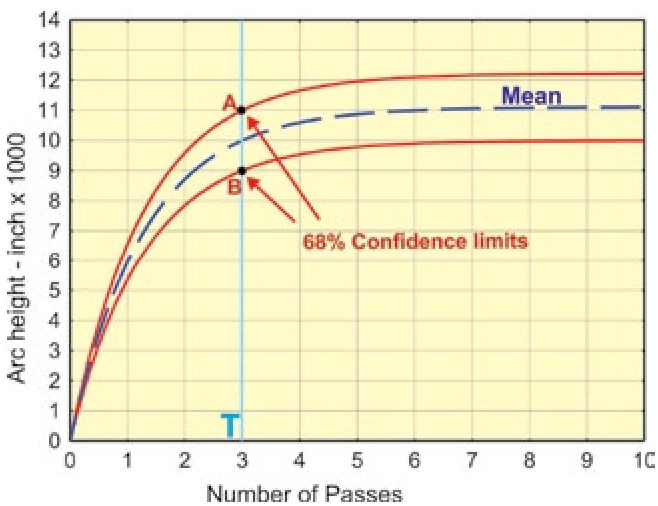

Fig.7. Example of saturation curve range with a peening intensity standard deviation of 1.

The curves in fig.7 have a scatter that has a standard deviation of 1 (imperial unit). This implies that more than two-thirds of the peening intensities would lie within ±1 (imperial unit) of a target figure of 10. If the customer requirement was 8 – 12 most shot peeners would (presumably) be quite happy with that sort of predictable range.

Almen strip variability has two quantifiable components: mean and standard deviation. Thickness, elastic modulus, pre-bow, steel composition and steel hardness are readily-identifiable factors that contribute to strip variability. A clear distinction must, however, be made between batch variability and inter-batch variability.

Thickness Variability

SAE J442 specifies allowed ranges of thicknesses for **N**, **A** and **C** strips. The process variables associated with strip manufacture are unlikely to vary substantially within the short time scale needed to produce one batch of strips. This is particularly true for strip thickness. Cold-rolling of steel strip is a well-established precision operation. Strip manufacturers can, therefore, obtain individual batches of strip material that have virtually constant thickness. There will, however, be differences between the mean thicknesses of any given batch. The difference is illustrated by fig.8. This assumes that the mean thickness of two acceptable N strip batches, A and B, is 0.77 and 0.80mm respectively and that both have the small thickness standard deviation of 0.001mm.

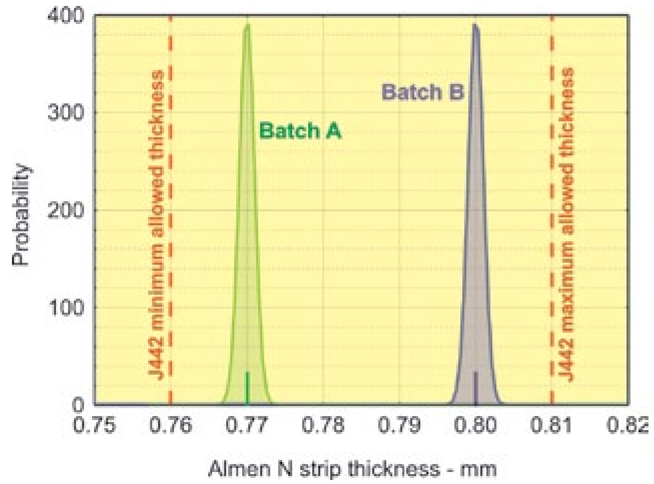

*Fig.8 Thickness distributions of two acceptable batches of **N** strips.*

A very important question is "Is the difference in mean thickness between batches A and B significant?" The answer is an emphatic "Yes".

For a given amount of shot peening the generated arc height reduces as the square of the strip thickness increases.

For the **N** strip example shown in fig.8 the measured peening intensity would vary by 7.5%, 6.0% for **A** strips and 2.5%. for **C** strips Referring back to fig.7 the mean peening intensity of 10 (imperial units) would be 7.5% different if Batch B strips were substituted for Batch A strips – and vice versa. A 7.5% difference corresponds to 0.75 in terms of mean arc height. That is significant.

Producing a saturation curve using a mixture of Batch A and Batch B strips would broaden the 'scatter band' of saturation curves. That is why manufacturers exhort users to "only use strips from a given batch when producing a saturation curve".

Elastic Modulus Variability

The arc height induced in any given strip is directly proportional to the elastic modulus of the strip. SAE J442 only requires that the Almen strips be produced from SAE 1070 cold rolled spring steel. SAE 1070 has a range of allowed carbon contents and stated elastic moduli – 190 – 210 GPa. Of itself, that range of elastic moduli would be equivalent to ±0.5 (imperial units) for the reference example shown as fig.7. The quoted elastic modulus range does not allow for the variations of preferred orientation induced by mechanical working of the strip steel. Steel has an anisotropy factor of 2.5 meaning that the elastic modulus can vary by a factor of up to 2.5 as working changes the randomly-orientated steel crystals into the equivalent of a single crystal's orientation. Aero strips use an aluminum alloy for which the orientation relative to rolling direction is specified.

Hardness

SAE J442 allows the hardness of **A** and **C** strips to vary by ±6% and that of **N** strips to vary by ±2.4%. Assuming that induced arc height is proportional to strip hardness then there could be a corresponding effect on the mean of a set of derived peening intensities.

Pre-bow

This is a well-recognized effect with SAE J442 restricting pre-bow to 0.025mm for **N** and **A** strips and to 0.038mm for **C** strips. The extent of pre-bow for any given strip is easily allowed for when producing saturation curves.

DISCUSSION

The availability of three different thicknesses of Almen strips normally allows users to adequately regulate the peening intensity that they require. There are, however, 'overlap regions' between **N** and **A** and between **A** and **C** strip usage. The study presented here indicates that **A** strips would be the preferred option for both overlap regions.

Dial pointer force has been shown to be an important factor when using **N** strips. This is based on equation (4) which predicts that measurable dial pointer deflections of **N** strips are to be expected – equivalent to a "pseudo double pre-bow". This can be allowed for by assuming that it is a genuine pre-bow. An alternative solution, particularly appropriate for aluminum-based aero strips with their lower elastic modulus, is to use a non-contacting displacement meter. The validity of the important equation (4) has been confirmed by employing the same push/pull spring balance described earlier. The procedure is illustrated in fig.9 and the earlier prediction that 140g of force would induce a 0.006mm deflection was verified exactly. **N** Almen strip deflections predicted in fig.4 were also verified.

Variability of measured strip response to peening is an ever-present problem when sourcing Almen strips. Eventually this comes down to the quality of strips purchased. "Caveat emptor" is a famous Latin legal phrase meaning "Let the buyer beware" - very appropriate when purchasing Almen strips. The best strip manufacturers expend a great deal of care in the selection of strip material, in the various stages of strip manufacture and employ in-house shot-peen testing using laboratory-standard peening controls. In practice, Almen strip batches can have a remarkable consistency. That is the converse of the sum of the possible variabilities presented in this article.

Consistency depends primarily on purchasing good quality strips. This can be complemented by regular checking of force gage reaction to a given batch of strips. The reaction to a given applied force may vary during the lifetime of a given Almen gage. One effective test is to use a force meter to initially measure and periodically check the force being exerted by the dial gage. Different displacements can be applied with a force meter so that the variation of resisting force with point travel can be checked.

Two areas have been highlighted that are not properly covered by specifications such as J442. The first is the actual elastic modulus of the Almen strips. This should be specified for actual strip material - rather than by relying on the single-condition value quoted for SAE 1070. A second, very significant, area is the thickness variability allowed for the three thicknesses of Almen strips. The thickness ranges quoted in J442 are the same ±0.025mm for all three thicknesses. This roughly equates to ASTM A109 and A568 tolerances which do, however, increase with the strip thickness of cold-rolled steel strip. A thickness range of ±0.025mm is crude when compared to the much smaller tolerances offered by numerous rolled-strip producers – such as those using cluster mills. If specifications such as J442 allowed a tighter tolerance grade of strip thickness then inter-batch variability problems would be greatly reduced.

*Fig.9 **N** strip reaction to known applied force.*