Strip Factors Influencing Almen Arc Height

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INTRODUCTION

Almen arc height is the deflection of the center of an Almen strip. This deflection, when caused by bombarding one face of the strip with high velocity shot particles, is used as a measure of the 'intensity' of the shot stream. Arc height, being such an important factor, is covered by several specifications, e.g., SAE J442 and J443.

Shot-peened Almen strips, on release from their fixture, adopt a curved shape, see fig.1. Arc height increases with the degree of curvature, **1/R**. Shot peening produces a compressively-stressed layer of depth, **d**. The stress in this layer, acting over the strip's cross-section, generates a force, **F**. This, in turn, imposes a bending moment, **M**, on the strip. The strip's resistance to the applied bending moment depends on its elastic modulus, width and thickness, **t**.

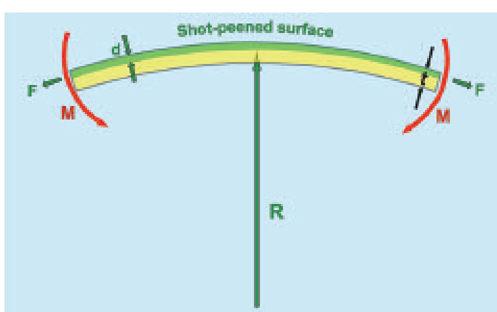

Fig.1. Curving of Almen strips induced by shot peening.

The strip factors that influence Almen arc height fall into two groups:

STRIP BENDING RESISTANCE, **E*I**, where **E** is elastic modulus and **I** is the 'rigidity factor' (technically known as the "second moment of area" of the strip) and

INDUCED BENDING MOMENT, **M**.

The greater the strip's bending resistance, the lower will be the observed arc height. The greater the induced bending moment the greater will be the observed arc height.

This article is an analysis of the several strip factors that affect bending resistance and induced bending moment. The reliability and consistency of Almen strips requires that all of the factors are controlled.

STRIP BENDING MODEL

Basic beam bending theory gives us a simple relationship between the bending moment applied to a beam and its consequent curvature, **1/R** :

$$1/R = M/(E*I) \qquad (1)$$

where **R** is radius of bending, **E** is elastic modulus, **I** is the 'second moment of area' and **M** is applied bending moment.

Equation (1) indicates that curvature (and therefore arc height) increases with increased bending moment but is decreased by increases in either elastic modulus or 'second moment of area'. Bending moment and elastic modulus are familiar parameters. 'Second moment of area' is less familiar. It is simply a quantitative measure of the rigidity of a beam. Fortunately Almen strips, because of their rectangular shape, have a simple relationship between 'second moment of area', **I**, and their dimensions:

$$I = w*t^3/12 \qquad (2)$$

where **w** is strip width and **t** is the strip thickness.

The significance of equation (2) can be appreciated by trying to bend a measuring rule. In one direction the rule bends easily. Turn the rule through 90˚ and it is virtually impossible to achieve visible bending.

If we substitute the value of **I** given by equation (2) into equation (1) we get:

$$1/R = 12M/(E*w*t^3) \qquad (3)$$

Curvature is not arc height, so that a relationship between them is needed. Use of the 'intersecting chord theorem' gives that:

$$h = s^2/(2R) \qquad (4)$$

where **h** is arc height and **s** is the distance between the support balls of the Almen gage.

Substituting for **R** from equation (4) into equation (3) gives:

$$h = 6s^2*M/(E*w*t^3) \qquad (5)$$

Equation (5) is a 'definitive equation' that indicates the inter-relationship of all of the significant strip factors. **s** is a parameter set by the Almen gage, **M** is a function of both shot bombardment and strip deformation, **E** is a strip function that curiously has attracted little attention, **w** the strip width is far less significant than is **t** the strip thickness.

ALMEN STRIP BENDING RESISTANCE

The bending resistance of an Almen strip is directly proportional to **E*I**, see equation (1). Both **E** and **I** are properties that should remain virtually constant from strip to strip – for a given grade of thickness N, A or C. In spite of its fundamental importance the factor **E*I** is rarely monitored directly.

A simple modification to a digital Almen gage allows it to be used to evaluate **E*I**. One such modification is illustrated in fig.2 where 5·5mm diameter steel rods are used to support a strip carrying a load, **P**. The rods prevent contact of the loaded strip with the normal support balls – obviating excessive wear. Deflections of up to 0.700mm can be monitored - before bent strip touches support balls. Rod separation is maximized to 71mm, using spacers at **F**, in order to give greatest deflection sensitivity. The appropriate 'bending of beams' formula is that:

$$h = \frac{P*s^3}{48E*I} \quad (6)$$

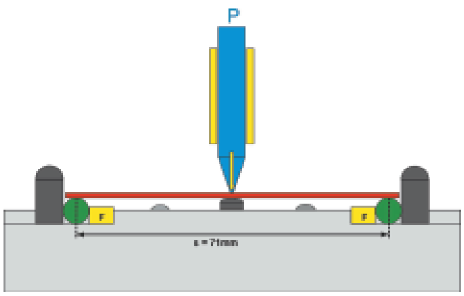

Fig.2. Modification of Almen gage for bending resistance measurements.

Substituting assumed values for **s**, **E** and **I** into equation (6) indicates that a load, **P**, in the range of 1–10N (about 0.1 – 1kg) should be sufficient to give a reasonable amount of N-strip deflection. The load, **P**, in fig.2 can be applied by various means. This modification employed vertical steel bars, of different masses, with chisel ends guided to the central loading line. A particular make of Almen gage needs to be 'propped up' to ensure that the strip is fairly horizontal in both directions.

Equation (6) indicates that there should be a direct correlation between deflection, h, and applied load, P. The modified Almen gage was validated by applying a series of loads to an A strip. Fig.3 shows the excellent linearity between deflection and applied load.

A number of tests can be carried out using the modified Almen gage. The most important commercial test is that for consistency of strip bending resistance. Academic tests include the comparison of bending resistance for the different thicknesses of N, A and C strips and evaluation of the elastic modulus.

Consistency Testing

As an example, a consistency test was carried out on a box of 50 Almen N strips. The same 758g load (7.44N) was applied centrally to each strip. Deflections were recorded using a TSP-3 Almen gage modified as illustrated in fig.2. The collected data is presented in bar chart format as fig.4.

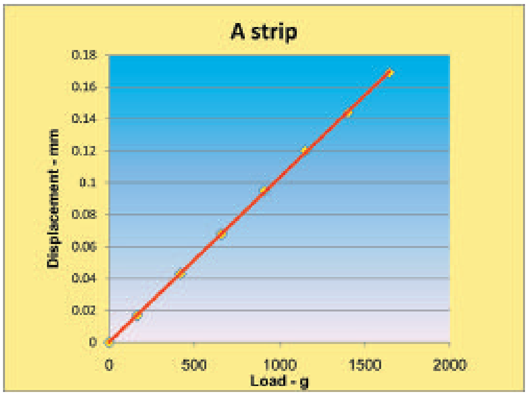

Fig.3 Linear relationship between load and displacement for Almen A strip.

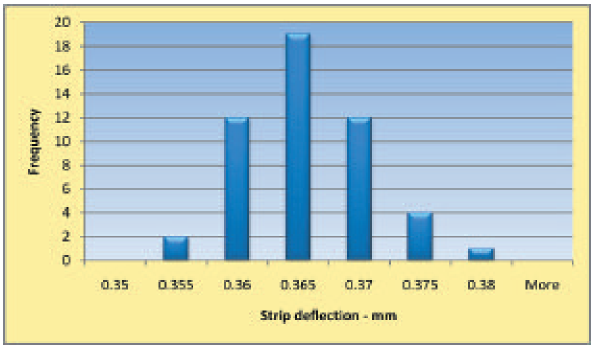

Fig.4 Bar chart showing frequency of deflections for 50 Almen N strips.

For fixed values of **P** and **s** equation (6) shows that there is a direct connection between deflection, **h**, and bending resistance, **EI**. The greater the variability of **h** the greater is the variability of **EI**.

In this test the standard deviation for the 50 deflection values was 0.0052mm, about a mean of 0.3633mm and the range was 0.355 to 0.376mm.

Effect of Almen Strip Thickness on Bending Resistance

The effect of strip thickness can easily be verified **IF** (it is a big "IF") **E**, **P** and **w** are constant. Under those restrictions equation (5) shows that the ratio of deflections h_1/h_2 for Almen strips of thicknesses t_1 and t_2 will be given by:

$$h_1/h_2 = (t_2/t_1)^3 \quad (7)$$

For a fixed load of 758g the observed deflections for single N and A strips were found to be 0.360 and 0.079mm respectively. Measured thicknesses for the strips were 0.784 and 1.293mm respectively (based on the average of 10 differently located measurements per strip). h_1/h_2 is therefore **4.56** and $(t_2/t_1)^3$ is **4.49**. The difference is 1.5% which is greater than the level of experimental error. Measurements showed that the two strips had precisely the same width. Exactly the same load had been used, so that the only remaining variability was of elastic modulus, **E**.

Effect of Elastic Modulus on Bending Resistance

Bending resistance is directly proportional to the elastic modulus of the strip material. Almen strips are manufactured from rolled SAE 1070 steel strip. The specified elastic modulus is 201GPa which is 4.5% lower than the average published value for ferritic steels of 210MPa. SAE 1070 can be supplied either as cold-rolled or hot-rolled wide or narrow strip. Published test values for SAE 1070 range from 190 to 219.4GPa.

It is not generally appreciated that the elastic modulus of rolled steels is a vector quantity, i.e., it has both magnitude and direction. Rolled steels are anisotropic - because of the grain preferred orientation that is induced. This anisotropy increases with the amount of rolling and is greater for wide strip than narrow strip. The frequency of intermediate annealing affects the amount of preferred orientation. Hot rolling with multiple passes produces a relatively-negligible amount of preferred orientation. N and A Almen strips are commonly manufactured by slitting and guillotining wide cold-rolled strip prior to heat treatment. Some C strips are manufactured from hot-rolled strip.

Anisotropy of elastic modulus will directly affect bending resistance. A limited test was therefore carried out to determine the elastic modulus of single, randomly-selected, N, A and C strip specimens. The slope of a best-fitting h/p straight line through the origin was used together with equation (6) and careful measurements of strip widths and thicknesses. Corresponding plots of deflection against load are given in figs.3, 5 and 6. Calculated values for the strips were:

N strip: E = 199.9GPa; A strip: E = 204.5GPa and C strip: E = 194.8GPa.

The three calculated values indicate that the elastic modulus, and therefore bending resistance, can vary significantly.

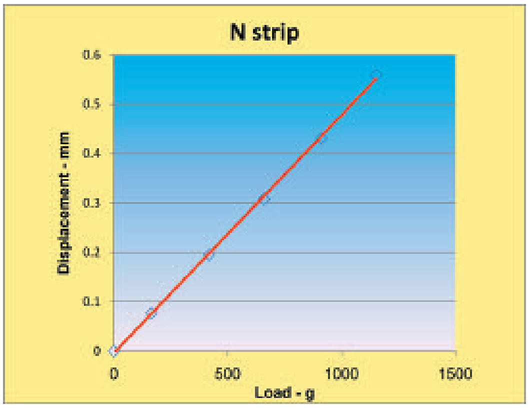

Fig.5 Displacement of N strip versus applied load.

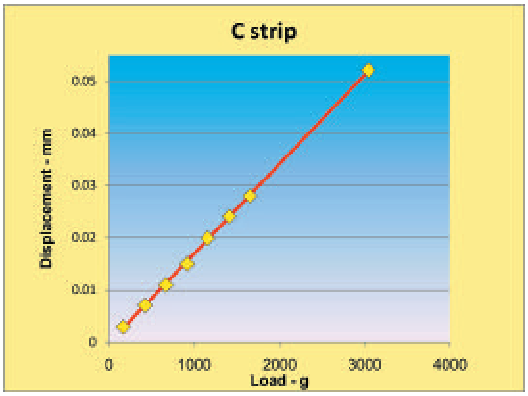

Fig.6 Displacement of C strip versus applied load.

INDUCED BENDING MOMENT

Shot peening of Almen strips produces a compressively stressed surface layer. The stress in this layer multiplied by the area over which it acts generates a force, **F**. This force, in turn, induces a bending moment, **M**. The resulting Almen arc height, h, is directly proportional to the magnitude of the bending moment, see equation (5).

Model of Bending Moment Generation

A simplified model of bending moment generation is shown in fig.7. The bending moment is assumed to be generated by a force, **F**, acting halfway down a compressed surface layer of depth, **d**. This bending moment is then **F(t – d)/2**. The force, **F**, is assumed to be the average stress in the compressed layer, **σ**, multiplied by the area over which it acts (strip width, **w**, times depth, **d**). **F = σ*w*d** so that the bending moment, **M**, induced by peening is given by:

$$\mathbf{M = \sigma * w * d * (t - d)/2} \tag{8}$$

The width, **w**, of Almen strips is virtually constant so that for a given thickness, **t**, of Almen strip there are only two variables in equation (8). Fig.8 shows predicted variations of bending moment with layer depth and stress level for an Almen A strip (width 18.95mm and thickness 1.295mm). The bending moment reaches a maximum when the compressed layer depth is half of the strip thickness. Thereafter the bending moment falls until it reaches zero of the compressed layer occupies the whole of the strip section. It will be shown later that specified restrictions on peening intensity mean that, in practice, the compressed layer would have a maximum thickness of less than 0.2mm. The bending moment is directly proportional to the average level of compressive stress, **σ**.

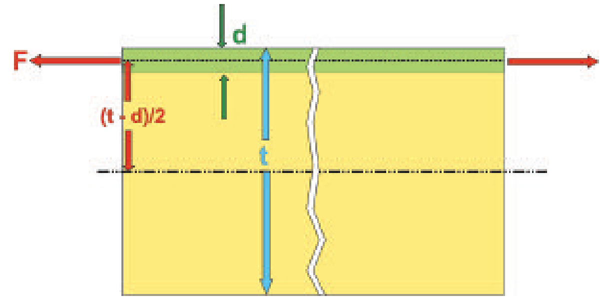

Fig.7 Schematic representation of bending moment generation in an Almen strip.

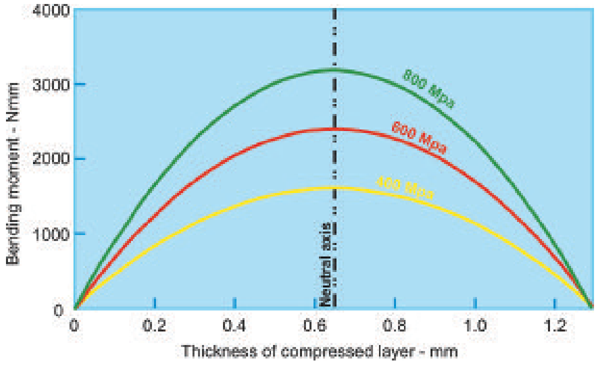

Fig.8 Effects of depth and stress in compressed layer on bending moment.

Effect of Strip Material Properties on Induced Bending Moment

The major property that might be expected to affect the induced bending moment is **hardness**. On the one hand a large hardness will lead to smaller indentations and therefore a smaller depth of compressed layer, **d**. On the other hand a larger hardness would be expected to result in a higher average level of compressive stress, **σ**, in the compressed layer. We therefore have opposing outcomes.

There is strong experimental evidence that the average compressive stress, **σ**, in a shot peened metal increases with increased hardness of the metal. The precise nature of this relationship has not yet been established for as-clamped peened Almen strips. A complication is present because Almen strips have a metastable tempered martensite structure. The greater the hardness the greater is the scope for 'peen tempering' (tempering induced by plastic deformation).

The diameter of shot peening indentations varies inversely with the fourth root of (Brinell) hardness. Depth of compressed layer varies directly with diameter of indentations. Hence it can be assumed that the thickness, **d**, varies inversely with the fourth root of strip hardness.

An empirical approach can be taken to combine the two opposing factors introduced by a strip hardness change. This approach has been used to produce fig.9. The data points are those presented by Champaigne and Bailey at ICSP9 – converted to percentage changes. The equation of a best-fitting straight line for those points has been added to the 'fourth root of hardness' equation to give the line "Increase due to increased layer stress". J442 specifies an allowed hardness range of 44 to 50 HRc. The predicted net change within that range would be 6.3%.

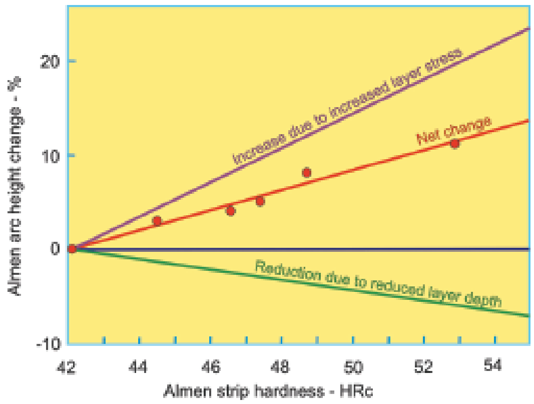

Fig.9 Combination of opposing hardness factors affecting arc height.

COMBINED EFFECTS OF BENDING RESISTANCE AND BENDING MOMENT ON ARC HEIGHT

The arc height, **h**, for a peened strip can be predicted (in mm units) by using equation (9):

$$\mathbf{h = 631{*}M/(E{*}I)} \qquad (9)$$

The bending moment, **M**, induced by peening is affected by the hardness, width and thickness of a strip - whereas the resistance to the bending moment, **E*I**, is affected by the strip's width and thickness as well as by its elastic modulus.

Equation (9) can be modified using the equations derived for **M** and **I** to give:

$$\mathbf{h = 3786{*}\sigma{*}d(t - d)/(E{*}t^3)} \qquad (10)$$

Equation (10) shows that the critical factors governing arc height are hardness (affecting **σ** and **d**), **elastic modulus and strip thickness**. The equation can be used to predict the effects of any of the several factors involved. Assuming, for example, that **σ = 800MPa** and **E = 201GPa**, equation (10) yields the curves shown in fig.10 for N, A and C strips (using average thicknesses). The curves reveal, for example, the virtual linearity of arc height versus layer thickness within the limits prescribed by J443.

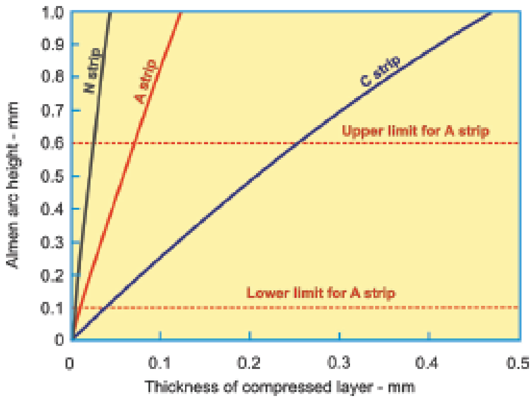

Fig.10 Predicted effects of strip and layer thicknesses on resulting Almen arc height.

DISCUSSION

A prime consideration for Almen strip manufacturers is that their strips' reaction to peening should be as consistent as is economically possible. Peening induces a bending moment whose magnitude depends on the hardness and thickness of a strip. The strip's resistance to this induced bending moment depends upon its elastic modulus, width and thickness. Measured arc heights, for a given amount of peening depend on five factors: hardness, thickness, elastic modulus length and width of a strip. The critical factors governing arc height are hardness, elastic modulus and thickness. Width and length control are needed in order that the curved strips can be accurately located on a gage relative to the support balls.

Specifications prescribe the allowed ranges of hardness, thickness, length and width for N, A and C strips. Surprisingly there seems to be no restriction on elastic modulus. The modification of a standard Almen gage described in this article allows elastic modulus to be measured with reasonable accuracy.

The analysis predicts that an increase of hardness will result in an increase in arc height – for a given peening treatment. This effect arises because the increased compressive stress level is more significant than the slightly reduced layer thickness. There is, however, a strong case for further experimental work to be carried out on the effect of Almen strip hardness on arc height.

A simplified bending of beams approach has been used for this article. A more rigorous approach would have involved complex mathematical procedures. It is believed, however, that this simplified approach is adequate for the intended purpose. Those strip variables that have a significant effect on arc height have been identified and highlighted.