ACADEMIC STUDY

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Almen Strip Quality

INTRODUCTION

Shot peeners are required to declare values of peening intensity derived at prescribed intervals. These values depend, to a significant extent, on the quality of the Almen strips that are being used. The primary factor defining "quality" of Almen strips is that they should be accurate. Accuracy is defined as a combination of bias and precision. Fig.1 illustrates the concept of bias. Imagine that there was some way in which we could know the "true value" of the arc height that should result from a fixed time of exposure to a fixed shot stream. If we then expose a batch of strips for the same time to the same shot stream, we may find that the mean value of the measured arc heights was different from the "true value". This difference is called "bias".

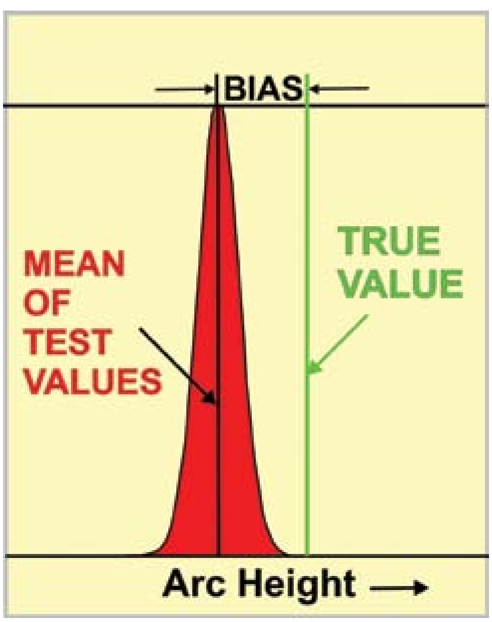

Fig.1. Bias exhibited by a set of Almen strips.

Fig.2 illustrates the complementary property of precision. The mean values of arc height for the two sets are spread over small and large ranges for high and low precision respectively.

A high accuracy for Almen strips therefore requires that they exhibit both high precision and a minimum of bias. Strip manufacturers have to cope, however, with a number of factors that can affect accuracy. This article presents the theoretical background to these factors. It is complementary to a comprehensive and fact-based study presented by Bailey

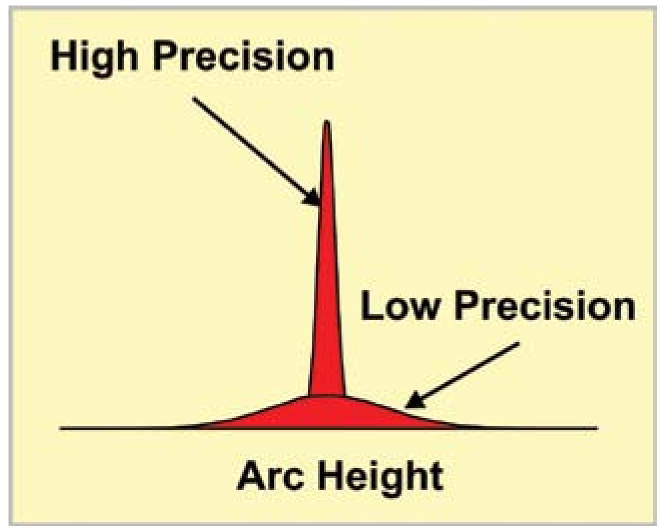

Fig.2. High and low precision exhibited by two different sets of Almen strips.

and Champaigne ("Factors that influence Almen strip arc height", ICSP9, 2005, pp392-399). Because of the large number of factors involved, some are dealt with here in much greater depth than are others.

Theoretical analysis of a quantitative topic necessitates the employment of mathematical techniques. Extensive use is made, however, of explanatory graphs. As the old saying goes: "Use a picture. It's worth a thousand words".

Most Almen strips are manufactured from SAE 1070 cold-rolled spring steel. Their allowed property ranges are described in J442. The strips themselves are key components in maintaining peening consistency. Primary defined variables include dimensions, chemical composition, hardness and elastic modulus.

It is concluded that a high level of accuracy can be, and is, achievable.

EFFECT OF ALMEN STRIP THICKNESS VARIATION

Almen strips, of necessity, vary in thickness to some extent. The effect of thickness variation can be estimated using the reasonable assumption that intensity, h, is inversely proportional to the square of strip thickness, t. That is because the rigidity (resistance to bending) of any rectangular strip is proportional to the square of the strip's thickness. Expressed mathematically:

$$\mathbf{h = K/t^2} \qquad (1)$$

where **h = peening intensity, K = a constant** and **t = strip thickness**

N Strip Estimations

(1) Assume that the "ideal" strip thickness for N strips is 0.79mm. As an example, further assume that the peening intensity is 0.100mm when employing this ideal strip thickness. Using equation (1) we have, ignoring units:

$$\mathbf{0.100 = K/0.79^2} \text{ so that}$$
$$\mathbf{K = 0.100 \times 0.79^2}$$

(2) Let us now assume that N strips are being used that are all 0.02mm <u>thicker</u> than the ideal, i.e., t = 0.81mm (the maximum allowed by J442). Using equation (1), together with the established value for K, we have that:

$$\mathbf{h^+ = 0.100 \times 0.79^2/0.81^2} \text{ or}$$
$$\mathbf{h^+ = 0.095}$$

This calculation tells us that measured peening intensity values will be reduced by 5% relative to the "ideal" if the strip thickness is at the top of the allowed range.

(3) Let now assume that the N strips being used are all 0.02mm <u>thinner</u> than the ideal, i.e., t = 0.77mm (the minimum allowed by J442). Using equation (1) together with the established value for K we have that:

$$\mathbf{h^- = 0.100 \times 0.79^2 /0.77^2} \text{ or}$$
$$\mathbf{h^- = 0.105mm}$$

This calculation tells us that measured peening intensity values will be increased by 5% relative to the "ideal" if the strip thickness is at the top of the allowed range. Taken together, we have the possibility of a 10% variation in measured peening intensity due simply to allowed variation in actual thickness of the strips. Note that this 10% variability is independent of the 0.100mm used in the specimen calculations.

Fig.3 is a graphical representation of the effect on declared peening intensity of strip thickness variation within the allowed range. This uses a precise relationship that applies irrespective of nominal peening intensity:

$$\mathbf{Devh^* - \% = -100(1 - 0.79^2/t^2)} \qquad (2)$$

Where Devh* is the deviation, as a percentage, from the intensity value that would have been derived if the Almen strips all had the "ideal" thickness of 0.79mm. The total possible range is 10%.

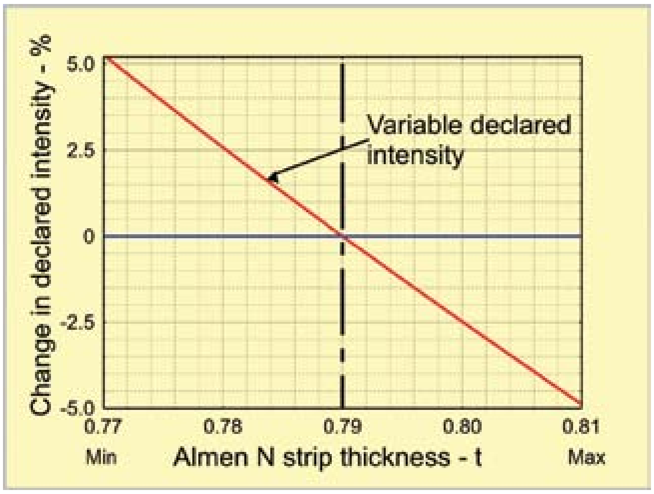

Fig.3. Effect of Almen N strip thickness variation on declared peening intensity.

A Strip Estimations

A strips are, of course, thicker than N strips. The thickness variation allowed by J442 is still ±0.02mm from an "ideal" thickness of 1.29mm. Estimates can be made by simply substituting 1.29 for 0.79 in equation (2) to yield:

$$\mathbf{Devh^* - \% = -100(1 - 1.29^2/t^2)} \qquad (3)$$

Where Devh* is the deviation, as a percentage, from the intensity value that would have been derived if the Almen strips all had the "ideal" thickness of 1.29mm.

The resulting effect is shown in fig.4 where the total possible range is now approximately 6%. This is predictably lower than that for the N strips because ±0.02mm is a smaller proportion of the greater strip thickness.

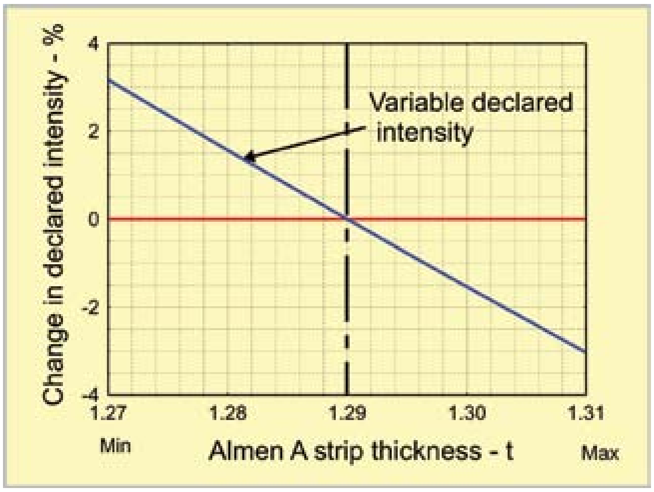

Fig.4. Effect of Almen A strip thickness variation on declared peening intensity.

C Strip Estimations

C strips are even thicker than A strips. The thickness variation allowed by J442 is now ±0.03mm from an "ideal" thickness of 2.39mm. Estimates can again be made by simply substituting 2.39 for 0.79 in equation (2) to yield:

$$\mathbf{Devh^* \text{ - } \% = -100(1 - 2.39^2/t^2)} \qquad (4)$$

Where Devh* is the deviation, as a percentage, from the intensity value that would have been derived if the Almen strips all had the "ideal" thickness of 2.39.

The resulting effect is shown in fig.5 where the total possible range is now approximately 5%. This in effect balances the larger allowed range of thickness and the greater value for the "ideal" thickness.

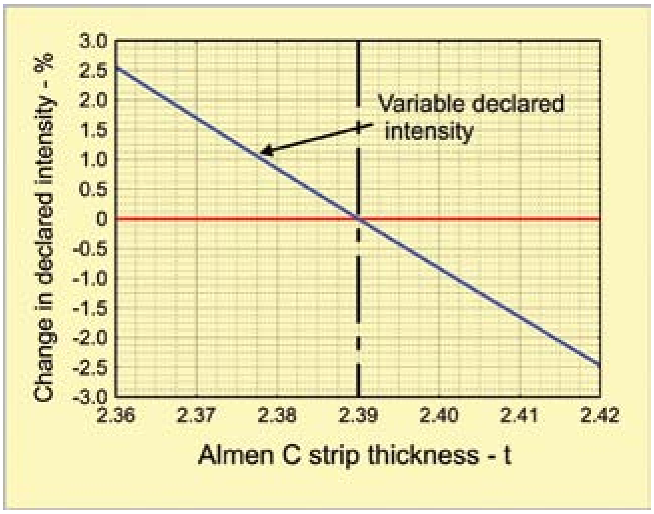

Fig.5. Effect of Almen C strip thickness variation on declared peening intensity.

Strip thickness is unlikely to vary for a given batch of strip material. It therefore follows that a significant amount of bias is possible and is more likely than a significant variation of precision.

EFFECT OF ALMEN STRIP LENGTH AND WIDTH VARIATION

SAE J442 allows a maximum variation of ±0.4mm for length and ±0.1mm for width from the "ideal" values of 76.0mm and 18.9mm respectively. Both length and width affect the rigidity of an Almen strip and therefore any arc height that will be induced by shot peening. The arc height, h, of any peened Almen strip has a simple relationship to the induced curvature, 1/R, of the strip (described in detail in the previous article in this series). This relationship follows from applying the "Intersecting Chord Theorem." Fig.6 illustrates the relationship.

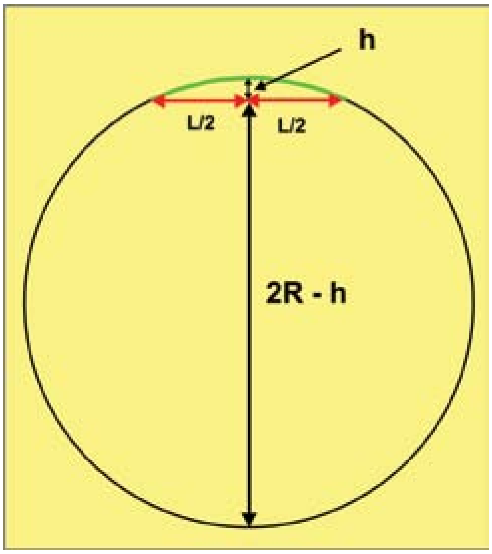

Fig.6. Intersecting chord theorem applied to an Almen strip.

Applying the intersecting chord theorem we have that:

$$\mathbf{h \times (2R - h) = (L/2)^2}$$

where L can refer to either strip length or strip width.

h is very small compared with 2R so that to a good approximation:

$$\mathbf{h \times 2R = L^2/4} \text{ or}$$
$$\mathbf{h = L^2/8 \times 1/R} \qquad (5)$$

As explained in the previous article in this series, 1/R = M/(E x I), where M is the bending moment induced by peening, E is the strip's elastic modulus and I is the strip's rigidity factor. Substituting this relationship into equation (5) gives that:

$$\mathbf{h = L^2 \times M/(8 \times E \times I)} \qquad (6)$$

Equation (6) applies to any peened strip. For the particular case when h is the peening intensity value, h*, we can say that:

$$\mathbf{h^* = L^2 \times M/(8 \times E \times I)} \qquad (7)$$

Equation (7) can be used to estimate the effects of allowed variations in strip length or width (as well as other factors as discussed later in this article). Using the same method as that used for estimating the effect of strip thickness, we get the variation shown in fig.7 (page 32).

The estimated effect of permitted Almen strip length variation is indicated to be some ±1.0% of the declared intensity value. As this effect is expressed as a percentage, it accommodates the fact that arc height is actually measured between gauge balls' contact.

Strip width and length are unlikely to vary for a given batch of manufactured strips. It therefore follows that a significant amount of bias is possible and is more likely than a significant variation of precision.

EFFECTS OF INDUCED BENDING MOMENT VARIATION AND STRIP PLASTICITY

For any given type of Almen strip (N, A or C), the magnitude of the induced bending moment, M, will vary with the metallurgical properties of the strip material. The major property variations are of **initial hardness** and **rate of work-hardening**. Fig.8 is a reminder of what is meant by bending moment in the context of Almen strip bending. Two factors contribute to the strip being bent to a radius, R. One is the compressive residual stress in the plastically deformed surface layer. The other is the plastic deformation itself. As pointed out in previous articles in this series, these factors contribute equally to a strip's bending. For any given shot stream, both factors are affected by the initial hardness of the strip. Points to note are that: (1) the harder the strip the less is the depth, d, of the plastically-deformed surface layer and (2) the harder the strip the greater is the average value of the induced compressive residual stress in this plastically deformed surface layer.

The effect of these two key points on the bending force, F, and depth, d, is illustrated in the schematic figs.9 and 10 based on residual stress distributions. Bending force is proportional to the area under the residual stress versus depth curve. A simple way to estimate this area is to draw a rectangle that appears to have a similar area. For fig.9 such a rectangle would have an area equivalent to 100N (200MPa x 0.5mm x 1mm) which is similar to an estimate of 90N (450MPa x 0.2mm x 1mm) for the curve in fig.10. These force values correspond to curve area multiplied by each millimeter of strip width.

The residual stress profiles shown in figs.9 and 10 are purely hypothetical, i.e., not based on any factual evidence. They are intended merely to illustrate that both the average level of compressive residual stress and the depth of compression are important for estimating the bending force.

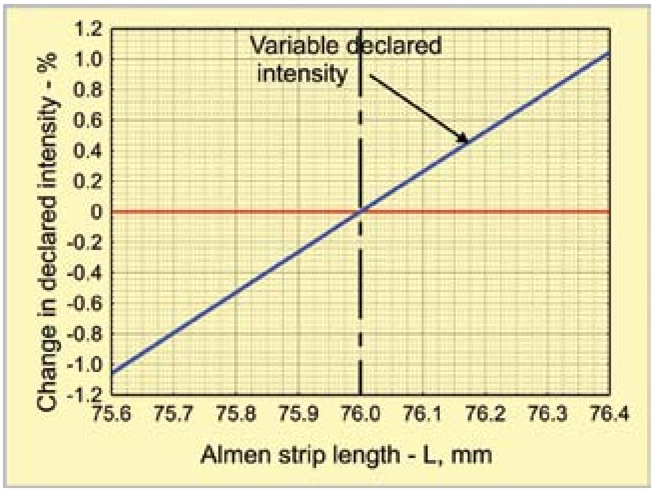

Fig.7. Effect of Almen strip length variation on declared peening intensity.

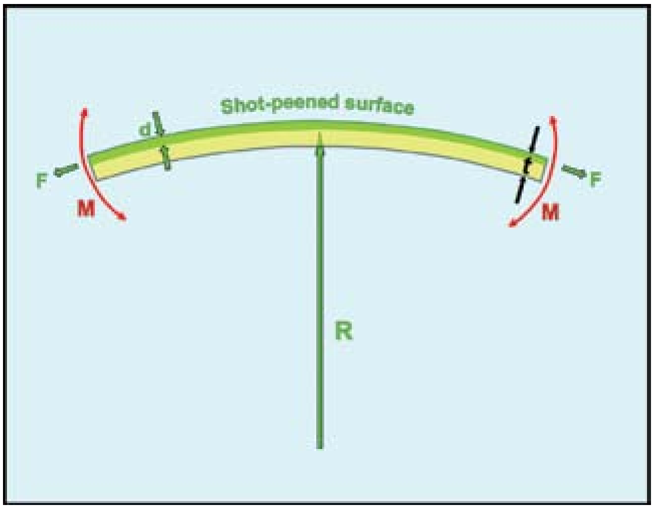

Fig.8. Bending moment, M, induced by force generated in shot-peened surface layer.

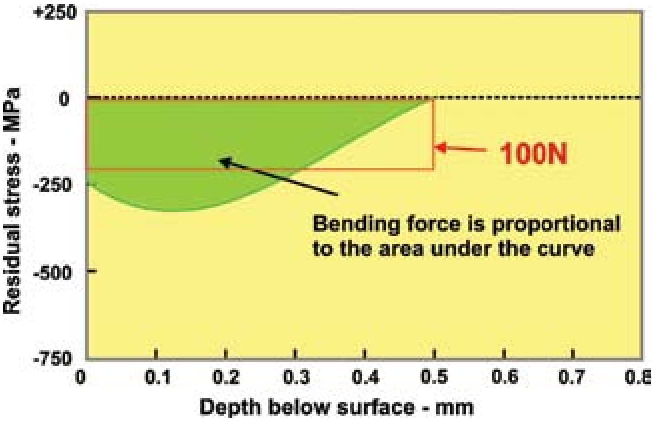

Fig.9. Bending force generation for relatively soft Almen strip.

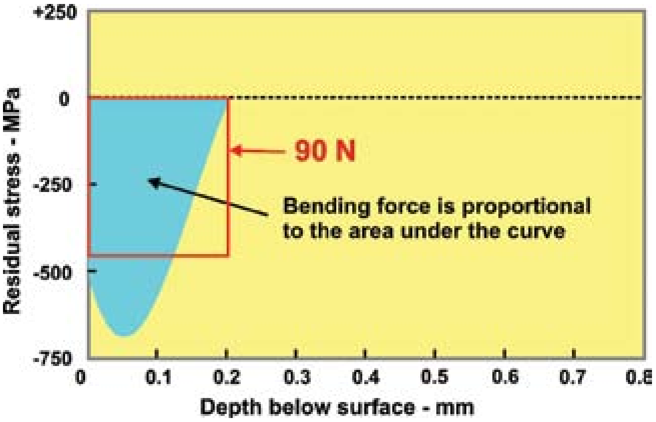

Fig.10. Bending force generation for relatively hard Almen strip.

We would expect that harder strip material would result in indents that have a smaller diameter. The Almen strip hardness range allowed by J442 is 44-50 HRC (72.5-76.0 HRA for N strips). 44-50 HRC is equivalent to Brinell hardness numbers of 409-481 (when using 3000kgf applied to a 10mm diameter ball). Using Brinell hardness is useful because it relates to the diameter of circular indents made by a ball rather than a shaped diamond.

The Brinell hardness relationship is given by the formula:

H_B = Applied force, P/(Surface area of the impression) (8)

Now the equation of the surface area of a circular indentation, also known as a "spherical cap", is quite complicated:

Surface area of the indentation = π*D/2(D – (D^2 – d^2)$^{0.5}$ (9)

where D is the diameter of the ball and d is the diameter of the indentation.

Substituting from (9) into (8) gives:

$$H_B = P/(\pi * D/2(D - (D^2 - d^2)^{0.5})) \qquad (10)$$

Fig.11 is a graphical solution of equation (10) for the maximum range of allowed equivalent hardness values (409-481 (when using 3000kgf applied to a 10mm diameter ball)). The curve is not quite linear. For a Brinell hardness of 409 (equivalent to 44HRC), the indent diameter is 3.02mm and for a Brinell hardness of 481 (equivalent to 50HRC), the indent diameter is 2.79mm. The difference in indent diameters is just over 8%. This is only relevant for the initial stages of shot peening. As peening progresses, we get multiple, overlapping indentations with corresponding work-hardening of the surface layer. The difference in hardness between the softer and harder Almen strips could then either decrease or increase!

It would be expected that higher levels of compressive residual stress would be induced in harder strip material than in softer strips. The corresponding bending force can be predicted using the "rectangle approach" used for figs.9 and 10.

The predicted bending force for the minimum allowed strip hardness is therefore proportional to 409 times 3.02 or 1235. For the maximum allowed strip hardness the predicted bending force is proportional to 481 times 2.79 or 1342. Arc height is proportional to bending force and 1342 is 8.0% greater than 1235. This leads to the theoretical prediction (in the absence of any other factors) that:

Almen strips with the maximum allowed hardness of 50HRC will give an 8% greater arc height than those with the minimum allowed hardness of 44 HRC.

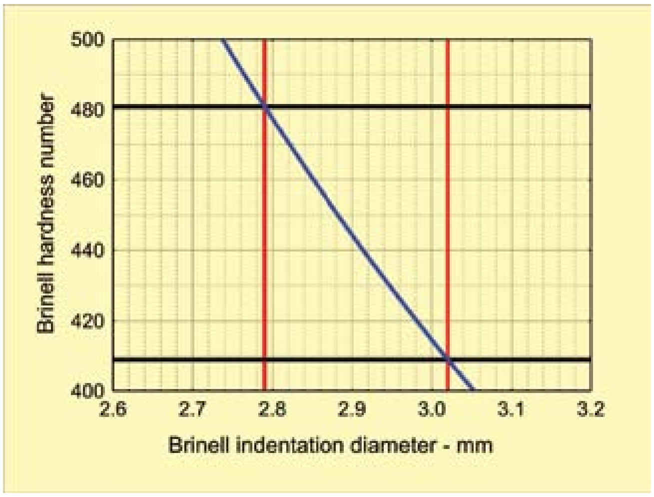

Fig.11. Variation of strip hardness affecting Brinell indentation diameter.

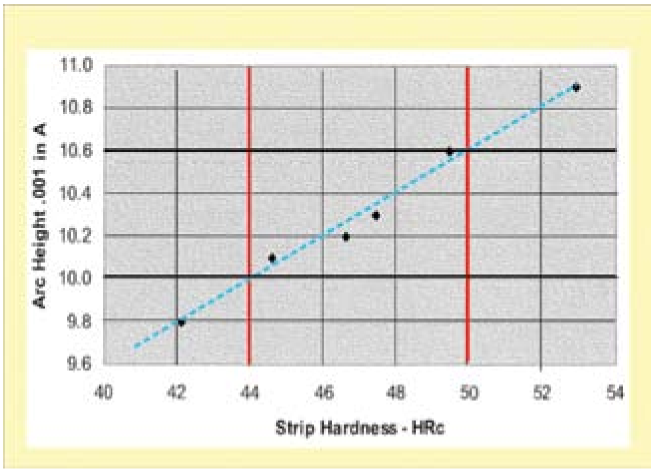

Fig.12. Effect of strip hardness on Almen arc height (Bailey and Champaigne).

Fig.12 is based on fig.1 of a paper presented at ICSP9 (P. Bailey and J. Champaigne, "Factors that influence Almen strip arc height", p392). Their results indicate a 6% increase (10.0 to 10.6) when strip hardness is raised from 44 to 50 HRC.

Fig.13 (page 36) represents the results of an internal EI study of the effects of strip hardness on arc height. This study involved a much wider range of strip hardnesses than that included in fig.12—the high hardness strips having been supplied by Toyo Seiko. The arc heights at the J442 limits could be calculated by inserting the range-limiting values into the fitted equations. Unfortunately, there appears to be an error in the stated polynomial equation. Using curve values obtained manually, the linear fit predicts a range of 17% for arc heights from 44 and 50HRC hardness strips. Substituting manually-obtained values for the best-fitting polynomial predicts a 9% range for arc heights from 44 and 50HRC hardness strips.

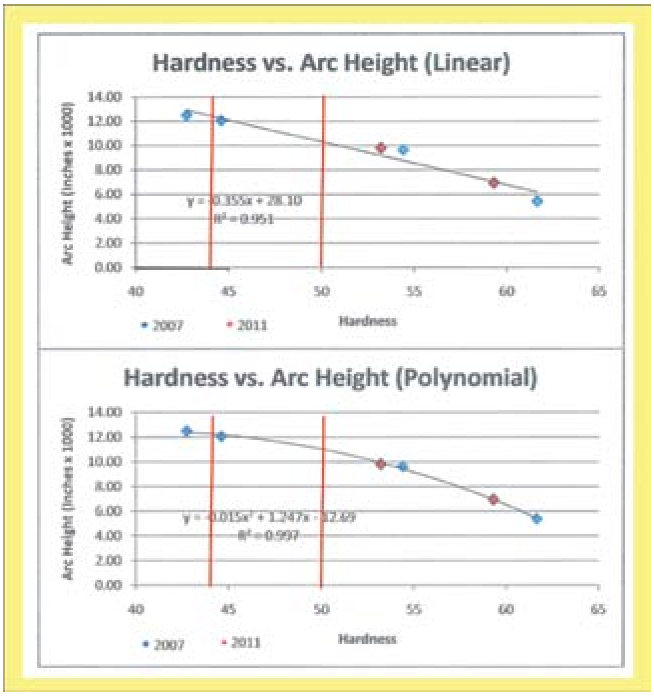

Fig.13. EI study of effect of strip hardness on curvature.

The fact that arc heights are consistent for a four-year interval indicates good precision. The predictions of either a 9 or 17% range of arc heights indicates that a significant bias can arise.

EFFECT OF ELASTIC MODULUS VARIATION

Arc height is inversely dependent on the magnitude of the elastic modulus, E. This is indicated in equation (6). The elastic modulus of 1070 steel can, reportedly, vary between 190 and 210GPa depending on the thermo-mechanical history of the strip. This would indicate the possibility of a significant bias —approximately 5%. Precision should, however, be good for a given batch of supplied strips.

EFFECT OF SURFACE FINISH

Polished Almen strips would be expected to lead to slightly higher arc heights for a given shot stream. That is because shot/surface contact angle is improved. Polishing is also relevant because it more closely represents the surface of most types of components. An EI study involving five different hardnesses of strip indicated a rise of from 12.0 to 12.3 (thousandths of an inch) as a consequence of using polished strips rather than unpolished strips.

DISCUSSION

The analyses that have been presented illustrate the significance of most of the variables that strip manufacturers have to cope with. Top-class manufacturers have strict control programs in place in order to ensure a minimum level of bias and a maximum of precision. Even without such programs there is a tendency for individual plus factors to cancel out minus factors. Premium-grade Almen strips are manufactured with rigid attention being paid to factors affecting quality.

Elasticity and plasticity properties govern material variability. Consistency can be checked by employing simple testing techniques. Fig.14 shows the force meter employed for the elasticity tests described in a previous TSP article (Fall, 2009). Fig.15 illustrates the principle of the ball-dropping plasticity test described in the TSP article of Summer, 2004.

Fig.14. Force meter gauging response of an Almen strip.

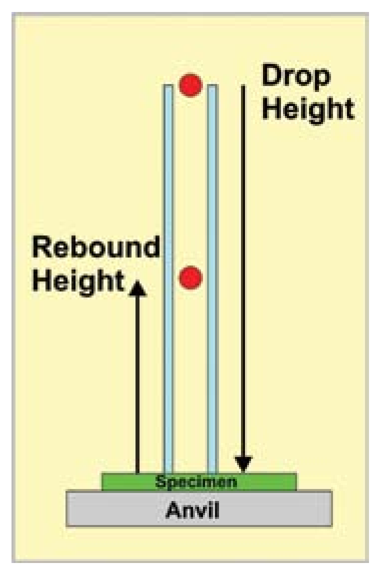

Fig.15. Ball-drop plasticity test principle.

In conclusion, it can be argued that the Almen Saturation Curve Test is still the most reliable method of gauging shot stream intensity. The strips themselves can be manufactured so as to display a minimum amount of bias and high consistency. A good case can be made for suggesting a halving of the current allowed thickness range for N strips. This would reduce the possible effect on deflection to the same as that currently possible for A and C strips.