Metrology of Almen Arc Height Measurement

INTRODUCTION

Almen arc height measurement is very important to the shot peening industry. The primary application is for determining acceptable shot peening intensity which uses ferromagnetic steel (SAE 107) strips. A secondary application, using paramagnetic aluminum alloy (2024-T3) strips, is for ensuring that excessive intensity is not applied during aircraft paint stripping procedures. The mechanics of Almen arc height measurement are very well documented. Almen strips, holders and measurement gage requirements are rigorously specified.

This article deals with the metrological principles of arc height measurement. The basic measurement components are the dial gage, strip holder and strip. Attention is focused on the significance of hold-down forces and ball wear.

DIAL GAGE

Arc height measurements are normally made using some type of dial gage. Dial gages have a long and honorable history within the engineering industry. Gages for measuring distance changes are generally either analog or digital. An example of a digital gage, sensitive to 0·001mm, is shown in fig.1. The facility for interface connection to a computer - so that readings can be fed directly to, for example, spreadsheets – has been incorporated. In this instance the gage is part of a basic facility for measuring peening parameters other than arc height – such as strip thickness variation, shot diameter, etc.

Fig.1. Digital gage with interface connection.

Interface connection reduces the chance of an operator introducing recording errors. Both types of dial gage have a spring-loaded shaft that exerts a constant force against the sample. The shaft travel is converted, using an internal rack and pinion system, into a rotary movement. This rotary movement is displayed directly on a dial for analog gages. Rotary movement for digital gages is converted into digital steps by a rotary encoder. Digital indicators can also be switched between imperial and metric units with the press of a button and may retain a 'memory' of a zero position. It is of fundamental importance that indicated shaft movements are very, very, close to actual shaft movements. Fig.2 shows the results of calibration tests on a TSP-3 Almen gage made by placing pairs of gage blocks on either side of the gage point. The gage block thickness range, of necessity, started just above the clearance between the support balls and the Almen gage body. A least-squares straight line fitted to the data is shown. The slope of the line, 1·005, reflects the required accurate relationship between shaft travel and shaft reading. The intersection of the line with the 'y-axis', -1·496mm, is the actual clearance between the check block surface and the gage body.

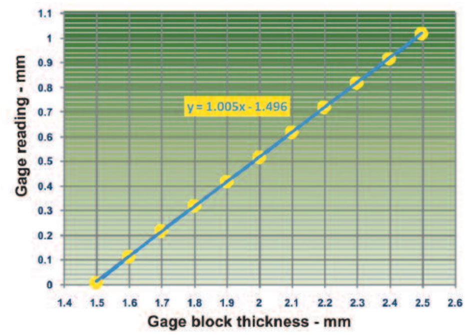

Fig.2 Calibration results on Almen gage made using gage block pairs.

Range, sensitivity, and shaft force are significant gage parameters for arc height measurements. A gage range of about 2.5mm/0.1" and a sensitivity of about 0.001mm/0.00015" would be appropriate. Much greater sensitivity would lead to annoying 'hunting' of the read-out. The gage indicator point may be flat, rounded or sharp. A specified roundness of point is appropriate for location against the concave side of a curved Almen strip.

Shaft force is a significant parameter for Almen arc height measurements. Digital gages have shaft forces normally within a range of 0·3 to 3N with the largest force being required to drive gages measuring the longest distances.

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A shaft force of about 0.5N is typical for commercial Almen gages. **0.5N** is the gravitational force that would be exerted by an object having a mass of **50g**. **N**, **A** and **C** Almen strips have masses of **9**, **14.5** and **27**g respectively. It follows that Almen strips must be held down if the gage shaft is pushing the strip upwards.

The dial gage acts in a comparator mode when in use for arc height measurements. Fig.3 represents this type of operation. A curved Almen strip induces a gage shaft travel to point **B** with a corresponding gage reading. We must have a second point **A**, in order to measure the distance between them – which in this case is our required arc height. The flat side of a 'calibration block' is generally used to provide this reference point – the gage being 'zeroed' when the block is in position. We would then have gage readings of **0** and **h** as shown in fig.3. The accuracy of arc height readings depends upon the accuracy with which both points, **A** and **B**, can be determined. It is good practise to have a second 'reference' flat block for periodically confirming the gage's zero indication.

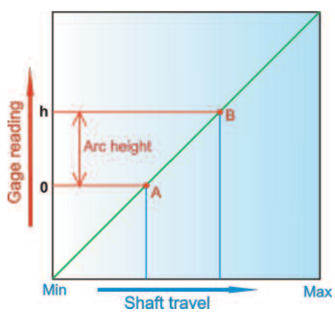

Fig.3. Dial gage comparator mode for arc height measurements.

HOLDER GEOMETRY

Gage specifications require that Almen strips are supported on four precision balls lying in a plane and at defined locations. These balls are crucial for maintaining precision of measurement. Ball material is normally either ferromagnetic steel or a ceramic. Fig.4 indicates the significance of the relative positions of strip, balls and peening block. An Almen strip is shown positioned on its four support balls. The contact points at A, B, C and D define the measurement plane, ABCD, which is on the unpeened underside of the strip. This plane is crucial because it determines both the gage zero and the arc height. It is worth noting how close the contact points are to the prior positions of the hold-down screws and to the strip edges – a matter of only 1-2mm! The heads of the screws will have shielded the strip from exposure to the shot stream. Strip edges will have received inhomogeneous peening. It follows that the strip must be positioned accurately relative to the support balls. Specifications require that two 'side stops' are provided and also indicate the positions of two optional 'end stops'.

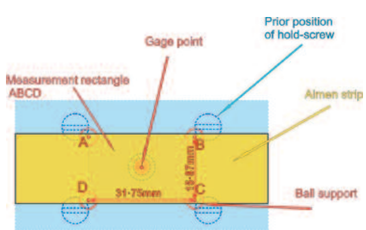

Fig.4. Representation of holder support geometry – to scale.

Fig.5 is a schematic representation of the holder stop locations with consequent tolerances. The side tolerance of 0·20mm is derived from the J442 Specification requiring the distance between the tangent to the side stops to be between 1·49 and 1·69mm from the edge of the strip. The required distance between the optional end stops is 76·9 to 77·4mm. If we combine that with the allowable length range of Almen strips of 75·6 to 76·6mm we get that the

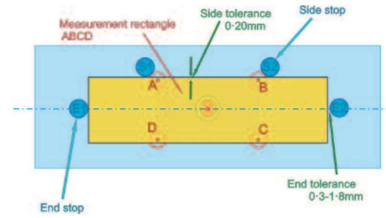

Fig.5 Side and end stop locations together with consequent tolerances.

end tolerance range is between 0·3 and 1·8mm.

HOLD-DOWN FORCES

Hold-down forces are required to hold strips and calibration blocks firmly in position relative to the four ball supports. The guiding principles are that (a) the thrust force of the dial gage must be overcome, (b) any bending moments applied during measurement must be negligible and (c) force location must be precise. Once positioned, movement has to be constrained so that dial gage measurements can be made at a fixed point – the centre of the measurement rectangle. Hold-down forces can be applied either mechanically or magnetically to ferromagnetic strips. The Almen strips used for shot peening intensity determination are ferromagnetic.

Fig.6 illustrates, schematically, the balance of forces that would be achieved IF the hold-down forces were only large enough to allow an Almen N strip to just touch the four support balls. Forces are shown to one decimal place. It is assumed that the dial gage exerts an upward thrust of

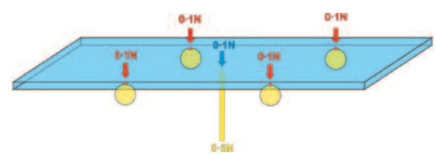

Fig.6 Balance of forces for Almen N strip just touching each support ball.

0·5N and forces are drawn as vectors (length indicating force magnitude). An Almen N strip, because of its mass of 10g, exerts a downward force of 0·1N directly over the gage point. The required balance of equal and opposite forces is achieved therefore by four 0·1N hold-down forces directly over the four support balls. With this situation the strip is not actually being held down in a practical sense – there are no upward forces at the four ball contact points to secure the strip in position.

Fig.7 (page 28) illustrates, again schematically, the balance of forces achieved when useful levels of hold-down force are applied.

FORCE, BENDING MOMENTS and DEFLECTION

The bending moment, **M** that a force, **F**, generates is the product of force and distance through which it acts, **D**. Hence we have that **M** is given by:

$$M = F.D \qquad (1)$$

An Almen strip has a rectangular section of width **W** and thickness **T**. Bending moments applied to a strip cause deflections that depend upon its rigidity. Rigidity, **I**, is given by:

$$I = W.T^3/12 \qquad (2)$$

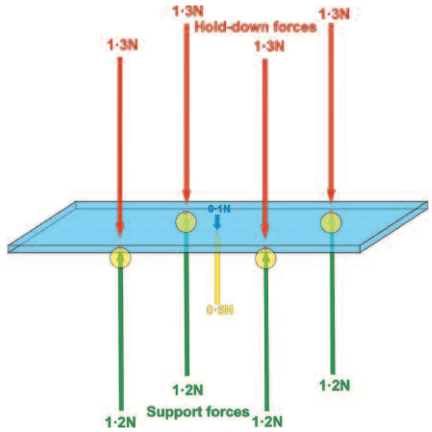

Fig.7 Typical actual hold-down forces and balancing forces.

Almen strips have thicknesses of about 0·8, 1·3 and 2·4mm for N, A and C respectively. Width is the same for all three at about 19mm. Corresponding I values are 0·8, 3·5 and 21·9mm^4. The ratios of rigidities are therefore 1:4:27. Any bending moments applied to an N strip will induce bending that is four times that which would suffered by an A strip and 27 times that for a C strip.

IF the hold-down forces applied to strips act **exactly in line** with the points of contact then they cannot exert a bending moment – the distance through which the forces are acting, **D**, is zero. Hence they cannot generate bending of the Almen strips. There is, however, one unavoidable bending moment. That is generated by the net force being applied by the dial gage point. Exact calculation of the deflection for five-point bending is complicated. Fortunately the problem can be simplified enormously by assuming that each pair of support balls acts at a single point. We then have three-point loading and the induced deflection **x** is given by:

$$\mathbf{x = P.L^3/(48E.I)} \qquad (3)$$

Substituting P=0·4N for load, L=32mm as distance between end support points, E=210,000Nmm^{-2} and I =0·8mm^4 predicts that, for an N strip:

x = 0·0016mm or 0·00006"

This dial-gage-induced deflection of an N strip is so small that it can only be detected using a sensitive Almen gage. Experimental confirmation of the predicted deflection was obtained by centrally placing an additional mass of 40g on a positioned Almen N strip. This mass generates a downward force of 0·4N counteracting the net upward 0·4N exerted by the dial gage. Twenty repeat measurements showed that the dial gage reading was reduced by 0·0017mm – confirming the accuracy of the preceding calculation. A and C Almen strips have rigidities four and twenty-seven times that of an N strip so that for them dial-gage-induced strip deflection is too small to be measurable.

The forces indicated in figs.6 and 7 were measured directly using an Electronics Incorporated TSP-3 Almen gage. 76mm by 19mm non-magnetic strips of various masses were piled up until the dial gage was just able to read zero. The pile of strips was then weighed as being 51g – indicating a dial gage force of **0.5N**. Sets of 10 Almen strips were weighed using 'letter scales' (accurate to 1g) to obtain average masses of **9**, **14.5** and **27**g for **N**, **A** and **C** Almen strips respectively. An accurate spring balance (scale 0 to 1000g) was connected using a string harness attached to positioned Almen strips. Raising the spring balance progressively counteracts the hold-down force until a given strip is pulled off the magnetically-energized support balls. The 'pull-off force' was about **4·8N** (490g times 0·98 for gravity) regardless of strip thickness.

The magnitude of mechanically-applied hold-down forces depends upon individual manufacturer's design. Magnetically-induced hold-down forces of necessity act precisely at the strip/ball contact points. Accuracy of load location is crucial for mechanical gages.

AERO STRIPS

Paramagnetic aluminum alloy (2024-T3) strips are used for aircraft paint-stripping control. These have the same dimensions as Almen N strips but the elastic modulus is much lower, at 73GPa, than the 210GPa of steel shot peening Almen strips. Applying equation (3) predicts that a dial gage force of 0·5N (the lighter mass of aluminum alloy strips having been neglected) would induce a strip bending deflection of 0·005mm (0·0002"). Such a small deflection can be ignored since paint stripping specifications typically require abraded strips to show less than 0·127mm (0·005") deflection.

Hold-down forces must be applied to paramagnetic strips mechanically – either directly or indirectly. The EI TSP-3AA Aero gage employs an ingenious hold-down device. Four spring-loaded pins press against the aero strip at points directly opposite each support ball. This device is located precisely by sliding down four parallel posts – which also act as the end and side strip stops. The springs display an increase in force that is a linear function of displacement – as with a spring balance. Dead weight loading of the pins indicated that the total force exerted when the device 'bottomed-out' was 3·9N – rather less than the total of 5·2N magnetic force exerted by the standard Almen gage.

HOLD-DOWN FORCE OFFSET AND ITS SIGNIFICANCE

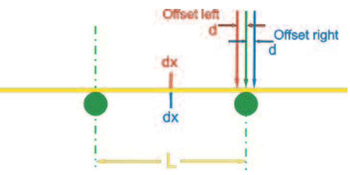

Fig.8. Offset hold-down forces generating strip displacements, dx.

For all types of Almen gage that apply hold-down forces mechanically there is the question of force application accuracy and its significance. Each hold-down force is offset a tiny distance (however small) away from the contact point between strip and support ball. An exaggerated situation is illustrated in fig.8 with two strip ball supports a distance **L** apart. The offset is **d** which will generate a negative displacement **dx** if it is to the left of the ball centerline (positive if it is to the right).

The induced deflection, dx, is given by:

$$\mathbf{dx = P.d(L^2 - d^2)/[9.\sqrt{3}.L.E.I]} \qquad (4)$$

Equation (4) can be used to predict the value of d that will give a stated value of dx. For example, we can choose the lowest measurable value for dx of 0·001mm, and substitute values of 2N for P, 32mm for L, 73,000Nmm-2 for E (hard aluminum alloy value) and I = 0·8mm4. That yields the prediction that d would have to be 0·44mm. For standard steel strips (E = 210,000Nmm^{-2}) the offset would need to be 1·28mm to give a measurable deflection. An identical offset to either right or left on BOTH support ball pairs would cancel induced deflections. If, on the other hand, one offset was to the left and the other to the right then the deflection would be doubled.

Fig.9 Photograph showing pin hold-down mechanism used for Almen Aero gage TSP-3AA.

The preceding calculations reinforce the need for mechanical hold-down to be precise – as with the Aero gage shown in fig.9.

SAMPLE SHAPES AND CONTACT POINTS

There are three shapes of sample surface used for arc height measurements. These are:

1. **Flat** – zero side of 'check block' and unpeened Almen strips,
2. **Single curvature** – curved side of 'check block' used to confirm dial gage readings and
3. **Double curvature** – peened Almen strips.

Flat samples will rest on the highest points of the four support balls. Samples with single curvature, on the other hand, will rest at some point **C** on a support ball, see fig.10.

The offset, **x**, can be estimated using equation (5). This equation was derived using a combination of 'Intersecting Chord' and 'Similar Triangle' theorems. The triangle **ABC** is 'similar' to one formed by the sample radius and L/2 so that:

$$\mathbf{x = 2.D.h_o/L} \qquad (5)$$

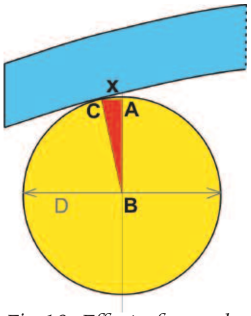

Fig.10. Effect of sample curvature on contact point.

where **D** is the support ball diameter, $\mathbf{h_o}$ is the arc height measured at the center of the strip and **L** is the distance between ball supports.

As an example: **D** and **L** are specified as 4·76mm and 31·75mm respectively and the standard EI 'Check Block' has a nominal arc height of 0·61mm. Substituting these values into equation (5) yields a value of 0·183mm for x.

The double curvature of peened Almen strips will induce two-dimensional off-sets for contact with the support balls. Fig.11 is an attempt to illustrate the difference between the contact points for the three sample surface shapes. Flat and single-curved samples will make contact at fixed points as shown for the plan view of a single ball (see position A in fig.5). Only the top part of the ball is included – because of the tiny off-sets involved. Peened Almen strips will make contact somewhere along the indicated track - depending on the arc height.

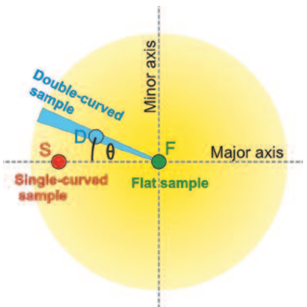

Fig.11. Schematic plan view of the top 0·5mm of one support ball showing different samples' contact positions.

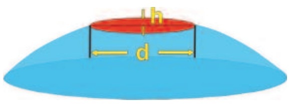

Fig.12. Ball wear flat (exaggerated) on top of support ball.

BALL WEAR DETECTION

Some ball wear is inevitable and increases with use. The major regions of wear will be the contact point areas **F** and **S** shown in fig.11. That is because the same points are contacted every time the 'check block' is used. The flat side of the block is normally used at least an order of magnitude more often than the curved side - being used for gage zeroing and pre-peening check of each strip. Most wear will therefore occur at point **F** on the top of each of the four support balls. This wear generates a 'flat' having a diameter, **d**, which reduces the ball diameter locally by an amount **h**, see fig.12. The relationship between **d** and **h** is given by the equation:

$$\mathbf{d = 2.\sqrt{(D.h)}} \qquad (6)$$

where **D** is the support ball diameter.

Equation (6) can be written in the form h = D^2/4D. **D** is nominally a fixed quantity – 4·76mm so that:

$$\mathbf{h = d^2/19.04} \qquad (7)$$

Equation (6) shows that when h = 0·001mm (smallest detectable value) and d = 4·76mm then d = 0·14mm. Hence, for wear to be gage-detectable the flat would have to be at least 0·14mm in diameter. When h = 0·002mm then d = 0·19mm, when h = 0·003mm then d = 0·24mm and so on. J442 requires that d has a maximum value of 1mm. When d does equal 1mm then equation (7) shows that h = 0·053mm (0·002").

The curved side of a standard Check Block can used as an accurate indicator of ball wear - up to a d-value of 0·37mm (being twice the radius value predicted by equation (5) for the Check Block). An alternative approach is to support the flat side of the check block on a pair of 1·500mm thick gage blocks, one on either side of the dial gage pointer, see fig.13 (b). The gage reading is compared with that without the gage blocks being in position, see fig.13 (a). For the author's TSP-3 Almen gage the **difference** is currently 0·006mm. Any further ball wear will increase the difference.

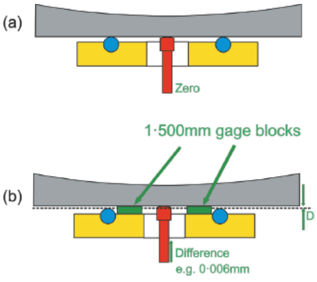

Fig.13. Ball wear test using 1·500mm gage blocks, 'difference' exaggerated for clarity.

PEENED ALMEN STRIP GEOMETRY

Peened Almen strips develop a fairly complex geometrical shape. Fig.14 is a schematic representation of the effect of this geometry on the measured Almen arc height, **h**. There are two components such that: $\mathbf{h = h_1 + h_2}$. The Almen strip contacts the support balls at four points defining the measurement plane **ABCD** (as in fig.4). Only the part of the strip shown in fig.14 contributes to the measured arc height – the rest is redundant.

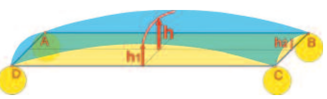

Fig.14. Schematic representation of the part of an Almen strip delineated by contact with the four support balls.

Two curves, longwise and crosswise, define the shape of a peened Almen strip. These curves for a complete peened Almen strip are illustrated by fig.15.

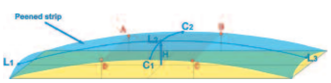

Fig.15. Complete peened Almen strip showing defining curves L1-L2-L3 and C1-L2-C3.

Measured arc heights are only a minor part of the maximum strip deflection, H, shown in fig.14. Fig.16 shows complete profilometer traces of the two curves L1-L2-L3 and C1-L2-C3 produced for a severely-peened N strip. The maximum deflection, H, is 2·97mm whereas a measured standard Almen arc height, h, is only 0·775mm. The latter is made up of h1 and h2 contributions of 0·506 and 0·269mm respectively. These contributions are in almost exactly the same ratio as that of AB/BC.

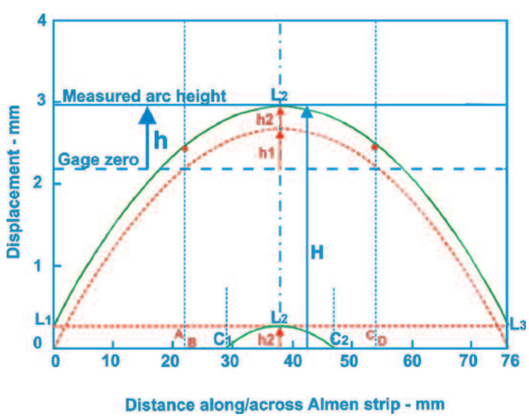

Fig.16. Profilometer analysis of Almen strip complete curvatures.

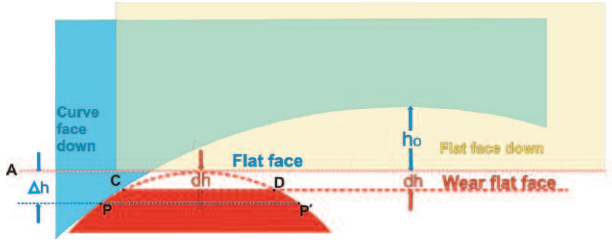

Fig.17. Effect of ball wear on arc height reading using Check Block, not to scale

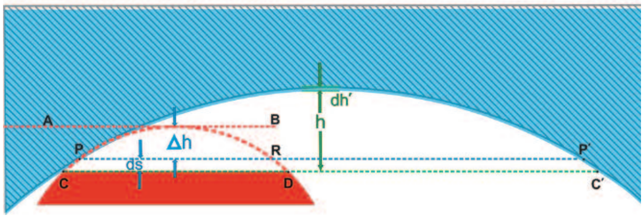

*Fig.18. Schematic representation of ball wear effect beyond normal contact point, **P**.*

EFFECT OF BALL WEAR ON ARC HEIGHT READINGS

(a) Check Block

The standard Check Block has a fixed, large, single curvature of one face. In the absence of any ball wear the flat face of the Check Block will make contact at the top of the balls along **A-B**, see schematic diagram fig.17. The curved face will make contact at some point, P, The corresponding gage reading will indicate that the arc height is $\mathbf{h_0}$. For single curvature $\mathbf{PP' = 0{\cdot}6{*}h_0}$.

With wear, the flat face of the Check Block will now make contact along the flat **C-D** (rather than along **A-B**). The indicated arc height reading will now be $\mathbf{(h_0 + dh)}$. As wear increases, **C-D** increases, so that **dh** increases. The curved face continues to make contact at the point **P** - it is only the flat side of the Check Block that changes its position. $\mathbf{dh = CD^2/(4D)}$, where **D** is the support ball diameter. For 4·76mm diameter balls we therefore have that:

$$\mathbf{dh = CD^2/19.04} \quad (8)$$

Equation (8) is valid up to **CD** reaching **PP'**. <u>Then</u> **dh** has a maximum value, **Δh**, as shown in fig.17. **PP'** for the standard Check Block is **0·37mm** (0·6*0·6096mm) so that **Δh = 0·007mm**.

If wear extends below the level PP' a different regime then operates. The curved face no longer makes contact at the fixed point, **P**, but at some lower point, C – see fig.18 – with a corresponding lowering of the Check Block. The Check Block position is shown 'hatched' for contact at **P** and 'plain blue' for contact at **C**. Again it is emphasized that the drawing is schematic.

For a wear flat diameter increase of from **PR** to **CD** the flat face of the Check Block has lowered by amount **ds**. The curved face has also lowered - by amount **dh'**. Net increase in **h**, **dh**, is given, for balls separated by 31.75mm, by: **dh = (CD – PR)/15·875**. Combining this with equation (8) gives a 'working equation', in mm, that:

$$\mathbf{dh = 0{\cdot}36{*}h_0^2/19{\cdot}04 + (FD - 0{\cdot}6{*}h_0)h_0/15{\cdot}875} \quad (9)$$

where **FD** is the wear flat diameter and $\mathbf{h_0}$ is the arc height in the absence of wear.

Equation (8) applies if $FD \leq 0{\cdot}6{*}h_0$. Equation (9) applies if $FD \geq 0{\cdot}6{*}h_0$.

Fig.19 (page 32) shows a plot for a standard Check Block (ho = 0·6096mm). Between **A** and **B** equation (8) operates and between **B** and **C** equation (9) operates.

The minimum detectable change (using a standard Almen gage) is 1 micron (0·001mm), when the wear flat has a diameter of 0·138mm. One manufacturer's recommendation is to limit allowed wear to 0·366mm – beyond this, the gage should be re-furbished – when the corresponding height change is 0·007(03)mm.

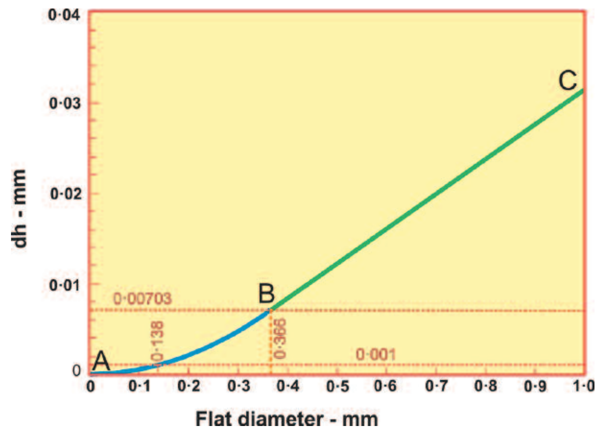

Fig.19. Effect of wear flat diameter on Check Block height reading.

(b) Peened Almen Strips

Peened Almen strips have a double curvature. The combined curvature varies considerably from strip to strip e.g. within a saturation curve set. The effect of wear flat diameter then depends upon the curvature. Strips with a very small curvature will make contact at the edge of the wear flat. Strips with a large curvature will make contact below the wear flat – as with the Check Block situation previously described.

The effect of wear flat diameter on a given set of peened Almen strips is illustrated in fig.20. A set of six strips have measured arc heights of 200, 240, 260, 275, 290 and 300 microns when the gage support balls have suffered zero wear. IF the gage balls had suffered wear then the effects on measured arc heights for each strip would be as shown. The larger the curvature the greater is the increase in corresponding measured arc height. Saturation intensity in the absence of wear is 258µ (based on peening 'times' of 1,2, 3, 4, 8 and 16 passes for the six strips). The increases of measured arc height, caused by ball wear, result in apparent saturation intensity values of 261, 265 and 273µ for wear flat diameters of 0·25, 0·5 and 1·0mm respectively (for the same set of peened strips).

DISCUSSION

Accurate Almen arc height measurement is a fundamental requirement for properly-controlled shot peening. The several factors that influence such accuracy have been analyzed. It has been shown that modern Almen gages accommodate all of these factors. It must be realized, however, that precision equipment demands careful, trained, usage if required accuracy levels are to be maintained. Gage calibration and veracity of zero measurements are very important. It is proposed that a separate flat calibration block should be specified for monthly cross-checking of the 'everyday' zero setting block.

Hold-down forces and specimen misalignment have been shown to have a measurable effect on measurements carried out on N strips. This effect is, however, very small and is normally only just detectable. The rigidity of thicker Almen strips means that the influences of hold-down forces and small misalignments are so small that they cannot be detected.

Magnetic hold-down of Almen strips has at least two significant advantages over mechanical hold-down. Hold-down force is applied at the top of each support ball and specimen manipulation is simpler. One disadvantage is that paramagnetic strips, such as those used for paint-stripping test requirements, cannot be held directly. Substantial involvement with paint-stripping justifies the purchase of a dedicated gage - such as the Aero gage TSP-3AA. Occasional involvement can be accommodated by using a simple modification. This is illustrated in fig.21. A simple 'raft' is shown - made from two 5mm diameter mild steel rods glued to a (ferromagnetic) C strip. The rod centers were separated by a distance of some 32mm (the separation of the support balls) during setting of the epoxy resin employed for gluing. Magnetic forces pull the raft onto paramagnetic specimens with sufficient force to hold them in position for arc height measurement.

Fig.21. Raft device for holding paramagnetic specimens on a magnetic hold-down Almen gage.

Almen arc height measurements are valuable, both immediately and for subsequent reference. They should all be stored in an appropriate computer database. The tedium of entering data manually is virtually eliminated if a computer interface device is employed to connect gage to computer.

Data-analysis programs can then be used to highlight any significant changes in, for example, zero calibration. Saturation curve analysis can be carried out directly on intensity data entered into a solver program.

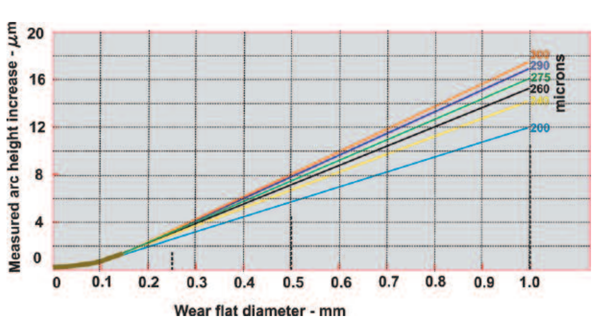

Fig.20. Effect of wear flat diameter on indicated arc heights for a set of peened Almen strips

Almen Saturation Curve Solver Program

FREE from The Shot Peener

Get the program developed by Dr. David Kirk

Request the program at www.shotpeener.com/learning/solver.htm