Accuracy of Declared Peening Intensity Values

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INTRODUCTION

Peening intensity is the arc height of one particular point on a simulated saturation curve that is declared as meeting specification requirements. Three stages are involved:
(i) **Generation of a Data Set** – Several Almen strips are given different amounts of shot peening and the induced arc height is measured for each peened strip.
(ii) **Simulation of a Saturation Curve** – the data set values are used to simulate a saturation curve that represents the continuous change of arc height with amount of peening.
(iii) **Declaration of Peening Intensity** – a particular point on the saturation curve is selected and declared to be the peening intensity value.

The definition of the term "accuracy" depends on its context. For peening intensity it may be defined as having three components:
(i) **Closeness to the true value**,
(ii) **Exactness of measurement** and
(iii) **Repeatability of measurement**.

Any consideration of peening intensity accuracy has to be related to the 'target intensity range' and its required accuracy.

Shot peeners, inspectors, users and equipment manufacturers have a shared interest in the accuracy of declared peening intensity values. This article attempts to present a detached analysis of the several factors that influence the accuracy of these values. It is shown that by far the greatest source of inaccuracy lies with the different interpretations of saturation curves allowed using current specifications. Declared peening intensity values vary by more than 10% for a given saturation curve - depending on the interpretation that is employed.

TARGET INTENSITY RANGE

Users specify a range of peening intensity values as a requirement that has to be met. Rather surprisingly this range does not have a specified accuracy. Fig.1 is a representation of a typical target intensity range – in this case 10-14 (using imperial units). As a target range, the values of 10 and 14 are exact quantities. Any declared peening intensity value less than 10 or greater than 14 fails to hit the target.

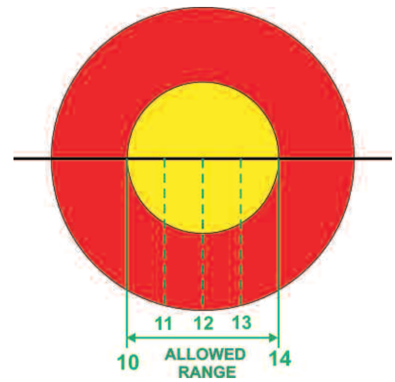

Fig.1 Representation of a Target Peening Intensity Range of 10-14.

Whether or not a particular declared peening intensity value hits a required target depends on the exactness of measurement. Assume, for example, that a shot stream's peening intensity is precisely 9.8758 (noting that we cannot actually measure to that degree of precision). If our measurement technique allowed two decimal places of exactness then that value would be rounded to 9.88 – failing to hit the target. With one decimal place of exactness the value would be rounded to 9.9 – again failing to hit the target. For no decimal places of exactness (using a crude measurement technique) rounding gives a value of 10 – now hitting the target!

Current measurement procedures normally declare peening intensity values to one decimal place of exactness. It would, therefore, appear reasonable that 'hitting the target' should be specified as a range with a minimum declared value of 10.0 and a maximum of 14.0. That implies, allowing for rounding, that the actual peening intensity was between 9.95 and 14.04. Allowing simple integral declared values would only prevent the actual peening intensity being acceptable if it was lower than 9.5 (rounding to 9) or higher than 14.4 (rounding to 15).

GENERATION OF A DATA SET

A typical data set of six strips, using imperial units for arc heights, is given in Table 1 on page 28.

Table 1 SAE Data Set No.8.

Time equivalent	Arc height inch x 1000
0.25	8.1
0.5	9.6
0.75	10.0
1	10.3
2	10.8
4	11.3

It is generally assumed that the 'time equivalent' values for every point in a data set are absolutely accurate. These values may be either integral numbers of passes/strokes or a reciprocal of the relative speed of the shot stream to the Almen strip fixture. The arc heights, on the other hand, cannot be absolutely accurate. "Closeness to true value" is largely a function of gage calibration. "Exactness of measurement" refers to the last significant digit of the measurement. This involves 'rounding' (which is carried out visually for analogue dial gages and automatically for digital dial gages). Hence, for example, the arc height for the first data point in Table 1 will actually lie somewhere between 8.050 and 8.149. 8.050 would be rounded-up to 8.1 and 8.149 would be rounded-down to 8.1. "Repeatability of measurement" is a function of both gage design and operator training/diligence. Even if the same peened strip is only being removed and replaced several times on a gage then the last significant digit will not always be the precisely the same.

'Rounding' is so commonplace that its significance is easy to overlook. **Rounded numbers carry with them the implication of exactness**. The third data point in Table 1 is shown, correctly, as having an arc height of 10.0. If, however, 10 had been entered that would have implied that the measured arc height was somewhere between 9.5 and 10.4 – rather than lying between 9.95 and 10.04. This is a small but important aspect of data presentation. Other important aspects of rounding are the avoidance of spurious exactness and spurious inaccuracy. For example, the average of three arc heights 10.1, 10.4 and 10.2 is 10.23333333, etc. To quote such exactness would be spurious (the arc heights themselves only being exact to one decimal point) so that the average should be declared as being 10.23. Spurious inaccuracy can occur when interpreting peening intensity times. For example, a peening intensity time, T, of 10.44 might well have been rounded down to 10.4. A 10% increase of this rounded-down time is 11.44 which, in turn, rounds down to 11.4. Increasing 10.44 by 10%, on the other hand, gives 11.484 which then rounds-up to 11.5. It is the 'double rounding' that has created the spurious inaccuracy of 11.4 - when the more accurate value is 11.5.

SIMULATION OF SATURATION CURVES

A continuous curve has to be simulated, using a small number of data points, as the second stage of peening intensity value declaration. This simulated curve can only be an approximation to the 'true shape'. This could only have been drawn if a large number of accurate data points had been available.

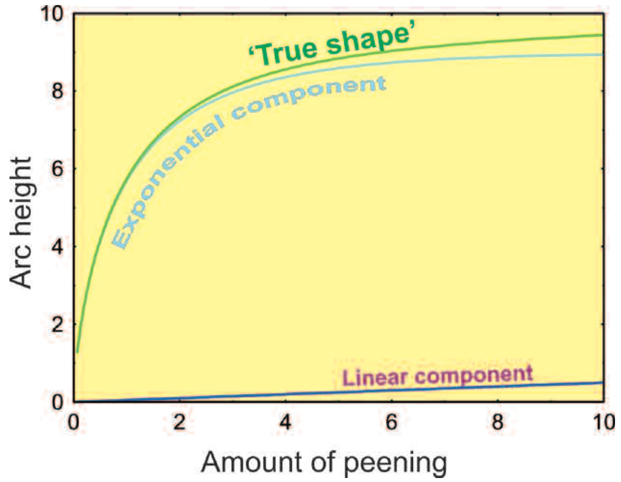

Fig.2 'True shape' of continuous saturation curve.

Fig.2 shows the 'true shape' for a shot stream that is constant in terms of peening intensity potential. It has been shown that this 'true shape' can be accurately represented by a combination of two components: three-parameter exponential and linear.

Hence:

'True shape' = Three-parameter Exponential component + Linear component

The mathematical equation representing the 'true shape' is:

$$\mathbf{h = a(1 - exp(- b*t^c)) + d*t} \qquad (1)$$

where h = arc height, t = peening time and **a**, **b**, **c** and **d** are constants.

Reliable simulation of the 'true shape' using equation (1) would require a large number of accurate data points. As a compromise, curve equations are selected that are simpler than that of the 'true shape'. Typical simpler shapes have the equations shown below:

$$\mathbf{h = a*t/(b + t)}$$
$$\mathbf{h = a(1 - exp(- b*t))} \text{ and} \qquad (2)$$
$$\mathbf{h = a(1 - exp(-b*t^c))}$$

A common feature of these simpler equations is that they all exponential – not having the linear component of a 'true shape' saturation curve.

The accuracy of simplified saturation curves depends upon three properties of the data set used in its production. These are:

(i) **Number of data points in the set**,
(ii) **Spread of the data points (in terms of amount of peening)** and
(iii) **Individual and collective accuracy of the data points in the set**.

Fig.3 shows an example of a data set that does allow accurate simulation of the 'true shape' of a saturation curve. The set has six, well-spread, accurate, data points. The data is an excellent fit to the 'true shape'equation (1) – indicated by the r^2 value of 0.99853 (r^2 is a commonly-used measure where a value of 1.00000 represents a perfect fit). An even better fit is obtained to the three-parameter equation **$h = a(1 - exp(-b*t^c))$** r^2 = 0.99866. A very good fit is also obtained for the two-parameter equation **$h = a*t/(b + t)$** - with an r^2 value of 0.98680.

The data set shown in fig.3 can be assumed to be accurate because it is a good fit to a 'true shape' curve. There is an obvious linear component to the 'true shape' curve. The other two curves shown are still very good fits – even though neither curve has a linear component.

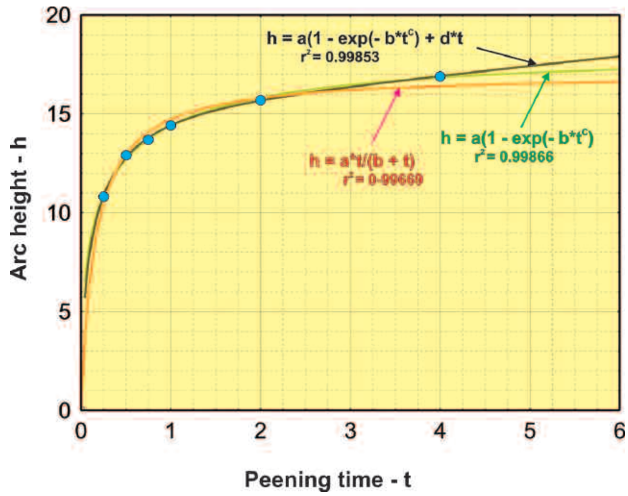

Fig.3. Data Set fitted to 'true shape' and rational function equations.

Fig.4 is for a data set that <u>could</u> have been obtained for the same shot stream that gave the data set used for fig.3. This four-point set has been deliberately chosen in order to illustrate the importance of number of points, data spread and point accuracy.

The data set has been fitted to each of the three exponential equations listed previously as equations (2). Different fits are obtained because (i) there are only four data points, (ii) the spread of points is poor – involving too high a proportion of long peening times and (iii) the individual point accuracy is poor because three successive points have almost the same arc height – rather than having a progressive increase in arc height.

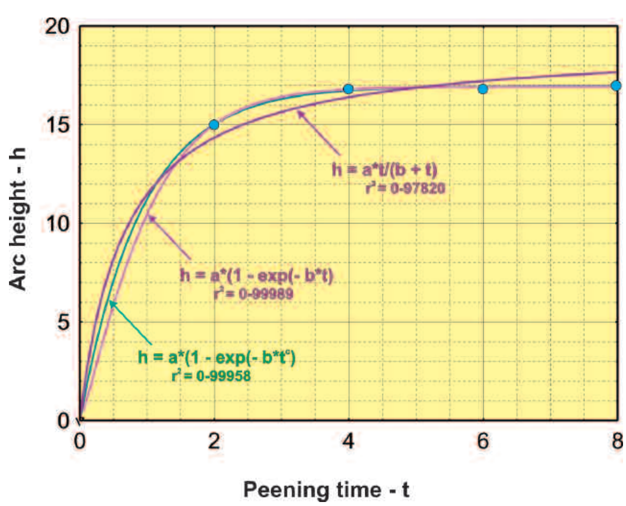

Fig.4. 4-point data set fitted to different equations.

It is important to appreciate that:

It is incorrect to assume that 'goodness of fit' implies accuracy.

Accuracy requires 'closeness to the true value'. Just because a set of data is a good fit to a particular shape of curve does not mean that that the data set is accurate. That aspect is illustrated in fig.4. The rational function **$h = a*t/(b + t)$** has the worst 'goodness of fit' but is probably the most accurate! The lesson to be learned is that data points should be fitted to a known shape of curve – not the other way round.

Manual simulation of a saturation curve is less accurate than computer-based curve-fitting, for several reasons: (i) the 'closeness to true value' is dubious because there is a natural tendency to draw a curve that is a good fit to the data points - rather than one having the known 'true shape' of a saturation curve, (ii) 'exactness' cannot be assured and (iii) 'repeatability' depends on who is drawing the curve.

DECLARATION OF PEENING INTENSITY

This third stage involves selecting one point on the simulated saturation curve to be the declared peening intensity. Selection can be achieved either by analyzing the simulated saturation curve or by simply choosing one of the data points. There are, however, three different definitions of "peening intensity" that can be invoked. These three definitions may be termed "10%", "Up to 10%" and "Not more than 10%, for Special Cases." Each of these will indicate a different peening intensity for the same shot stream!

1"10%" Peening Intensity Definition

The "10%" definition is **"the arc height <u>of</u> the point of a continuous saturation curve that increases by 10% when the peening 'time' is doubled."** "**of**" means a unique point of the simulated saturation curve – not a data point from the set used to produce the curve. The difference is illustrated in fig.5 where the peening intensity is declared to be "8.7". With this definition "increases by 10%" is meant to be exactly that – not a rounded value.

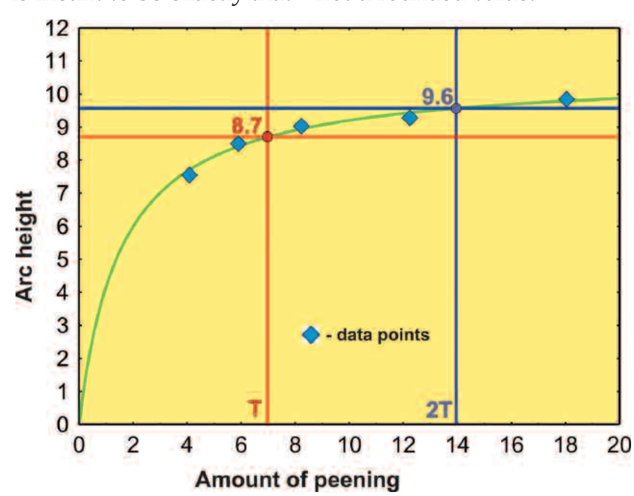

Fig.5 Unique peening intensity point of 8.7 at T.

The saturation curve shown in fig.5 was derived using a Solver 2PF program for a set of five data points. Determination of the peening intensity, shown as 8.7 occurring at a 'time' T, was carried out automatically. The point at which the intensity increases by exactly 10% is shown as 9.6 (to the nearest decimal point) occurring at the doubled time of 2T. Computer programs calculate the peening intensity point's position with enormous precision. It would, however, be bad practice to claim a higher precision than can be justified by that of the actual data points. Maximum accuracy is achieved by having a data set with points on either side of the declared peening intensity point.

Manual interpretation of manually-drawn saturation curves cannot, of course, involve the required 10% increase with the same exactness as can be achieved using a computer program. Having drawn a smooth curve on large graph paper it is, however, still possible to determine the "10%" peening intensity point with acceptable precision. The standard procedure is iterative – first guesses are made for T and the values of the curve at T and 2T are compared for nearness to a 10% increase. Using the curve shown in fig.5 for example, first guesses for T/2T might well be 6/12 and 8/16. 6/12 corresponds to an 11.4% increase whereas 8/16 corresponds to an 8.8% increase – one increase is too high and the other is too low. A second guess is therefore that 7/14 would be closer to a 10% increase than either 6/12 or 8/16. By coincidence the increase for 7/14 is precisely 10.0%. At the time, T, of 7 the curve's arc height is 8.7 with 9.6 at 2T – correct to the required precision. It should be noted that there is no question of an 'error band' being needed for the 10 in the 10% increase. Exactly 10% is used for the calculations. All that is needed is to arrive at a T/2T pairing that identifies the peening intensity value to the required exactness – normally to the nearest 0.1. A useful aid, that removes the need for calculating 10% increases, is a two-column chart. Arc height values appear in one column and 10% greater values in the adjacent column. Such charts are easily produced using Excel.

The process of selecting the required T/2T pairing can also be facilitated by the use of pre-printed transparent "10% graph paper" - an example of its application being shown as fig.6. A transparency is placed over chart paper containing the manually-drawn saturation curve. This curve is intersected by several of the "10% lines". The most appropriate line is the one that intersects at two 'amount of peening' points where one is twice the other. In fig.6 AB, the most appropriate line, has been highlighted. This intersects the manually-drawn curve at T and 2T. At T, the arc height is 8.66 which rounds to 8.7. Interpolation allows further refinement of the intersections so that 2T becomes very close to being twice T although it still yields the peening intensity to be 8.7 when rounding to one decimal place. The use of this aid may appear cumbersome but, with a little practice, identifying T and 2T becomes very quick. A 'workshop' version involves plotting the data and drawing the saturation curve using a graphed whiteboard. The "10% graph paper" transparency is then projected onto the whiteboard using an overhead projector.

The mathematical basis for "10% graph paper" is given as an appendix to this article. This allows anyone to produce their own copies.

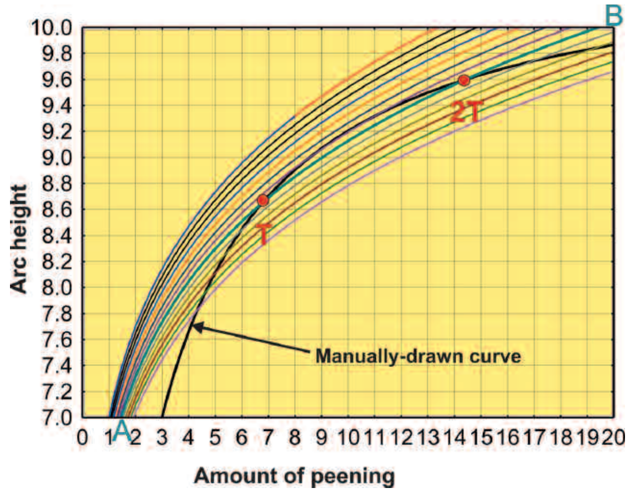

Fig.6 "10% graph paper" on top of a manually-drawn saturation curve.

The most important feature of the "10%" definition is that it leads to a single, unique, value of peening intensity.

2 "10% or less" Peening Intensity Definition

The "10% or less" definition is "**the arc height of the point on a saturation curve that increases by 10% or less when the peening 'time' is doubled**". This requirement is illustrated in fig.7. The same saturation curve as was used for fig.5 has been plotted but with an extended 'amount of peening' scale. Data points have been omitted – for clarity. Any pair of points, such as those shown as 14 and 28, can be used when applying the "10% or less" intensity definition – provided that the lower point is either at or to the right of A. This leads to the "10% or less" intensity curve as shown in fig.7. For the simulated saturation curve of fig.7 the peening intensity values that could be declared are anywhere between 8.7 and 10.6.

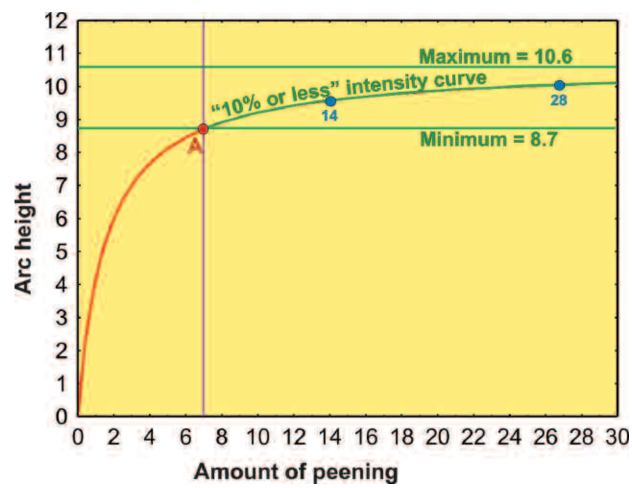

Fig.7 "10% or less" intensity curve.

It can be argued that, in practice, most users of the "10% or less" intensity definition would declare an intensity closer to the minimum available value than to the maximum available value – thus narrowing the "error band" of 8.7 to 10.6. Against that there is a probability that a saturation curve having large "amount of peening" times would not show an exponential flattening-out. The arc height tends to increase continuously, albeit slowly, with long peening times. It is probable that users of the "10% or less" intensity definition also construct saturation curves manually. The subjectivity of that procedure then increases the error band even further.

An important feature of the "10% or less" peening intensity definition is that the declared value is not unique, it can vary substantially for a given shot stream - introducing a substantial error band.

3 "Not more than 10%, For Special Cases" Peening Intensity Definition

There are some peening shop procedures where the minimum peening 'time' (one pass/stroke/rotation) that can be applied is longer than the time, T, of the unique point determined using the "10%" intensity definition. A third intensity definition is therefore sanctioned that is based on a schematic "Type II saturation curve". This type of saturation curve (similar to fig.2 in SAE Specification J443) is presented as fig.8. The corresponding J443 definition of intensity is quoted as follows:

" For type II saturation curves the intensity is defined as the arc height value of the first data point (i.e. at the minimum possible exposure time, t) provided that the arc height rises by no more than 10% when the exposure time is doubled – time 2t. The intensity shall be interpreted as the arc height value of the first strip reading."

A "type II" saturation curve is based on two assumptions. The first is that all of the measured data points have similar arc heights – so that a horizontal line is a reasonable representation. The second assumption concerns the variation in arc height prior to the first data point. This is shown as increasing linearly from zero until it intersects with the first data point (since it is not possible to establish a more accurate intersection point). For the quoted intensity definition the declared intensity is that achieved after one pass.

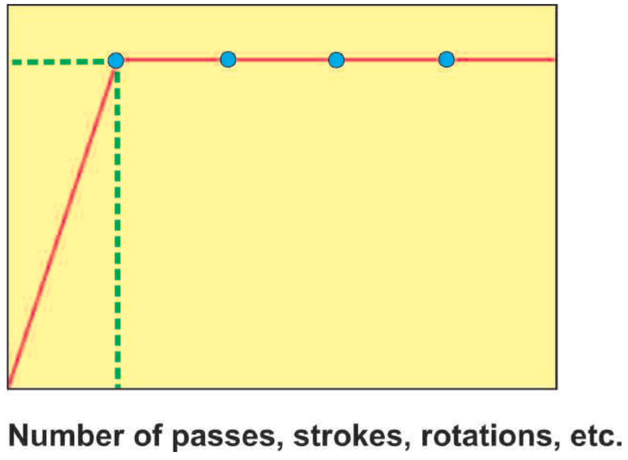

Fig.8 Type II saturation curve for "Special Cases."

The SAE presentation of a "type II" saturation curve is only 'schematic'. An actual set of arc heights for 1, 2, 3 and 4 passes would not normally be identical. Fig.9 illustrates the relationship between "Type I" and "Type II" saturation curves for a more realistic set of data points. "Type I" is the

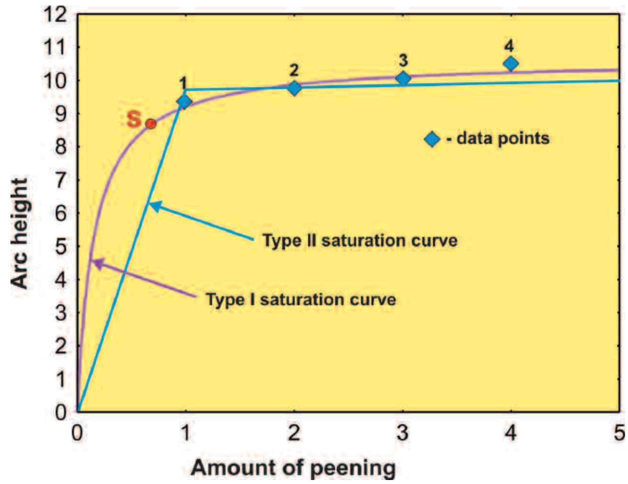

Fig.9 Comparison of normal saturation curve, type I, and "special case" curve, type II.

normal shape of saturation curve - that allows the derivation of the unique peening intensity point, S.

The first data point on a type II saturation curve can be anywhere to the right of S. It follows that the range of declared peening intensity points would be the same as when applying the "10% or less" definition described previously. In most real situations the first data point, 1, would not be anywhere near as close to S as in the example used for fig.9. Unlike the two previous definitions, the declared intensity value is that of a single data point. Any value based on a single measurement is less accurate than one that is based on averaging several measurements.

DISCUSSION

The accuracy of declared peening intensity values depends on the accuracy achieved at each of three succeeding stages: generation of data set, simulation of saturation curve and declaration of peening intensity. These are interdependent stages. If the data set is inaccurate then the two succeeding stages cannot rectify that inaccuracy. Poor simulation of a saturation curve (even when based on an accurate data set) will mean that an accurate declaration of peening intensity becomes impossible. Finally, even if an accurate simulation of a saturation curve has been achieved (based on an accurate data set) then there remains the problem of deciding which arc height on the curve is to be declared as the peening intensity value. For the same shot stream, the declared peening intensity value will vary by more than 10% - depending on which of three different definitions of "peening intensity" is invoked. This is obviously not a satisfactory situation.

Error bands are additive so that a definition-induced error band only makes life more difficult for shot peeners. The 'definition-induced error band' can easily be eliminated for Type I saturation curves by deleting the "10% or less" definition completely. Unique saturation intensity values can easily be derived by applying just the "10%" definition. Type II saturation curves, on the other hand, necessitate a different intensity definition. Overall, the use of just two intensity definitions would be a welcome clarification of a presently ambiguous situation.

Declared peening intensity values should be rounded to an agreed level of exactness - one decimal point when working in thousandths of an inch arc height. It should not be possible for a measured peening intensity value to be rounded to an integral value in order to satisfy a customer's stated range. For example, a measured value of 9.5 should not be allowed to satisfy a stated range of 10 -14.

Appendix

DERIVATION OF MATHEMATICAL EQUATION FOR "10%" GRAPH PAPER

The required feature of "10%" lines is that the y-value should increase by precisely 10% when the x-value is doubled. A starting position is to assume that the variation of y with x is of the type shown in equation (1) in which **c** is a constant:

$$y = x^c \qquad (1)$$

Doubling of **x** to yield a 10% increase in **y** can be expressed as equation (2):

$$1.1y = (2x)^c \qquad (2)$$

Equation (2) can be written as:

$$1.1y = 2^c.x^c \qquad (3)$$

Dividing equation (3) by equation (1) gives that:

$$1.1 = 2^c \qquad (4)$$

Applying logarithms to equation (4) gives that:

$$c = \log_2(1.1) \qquad (5)$$

Equation (5) is the required solution for the constant, **c**. It is that "**c** is the log to the base 2 of 1.1". The required mathematical equation for a series of "10%" lines becomes:

$$y = a.x^c \qquad (6)$$

where **a** is a variable and the constant **c** is equal to $\log_2(1.1)$.

The numerical value of the constant, **c**, is given (to five significant figures) by:

$$c = 0.13750 \qquad (7)$$

Substituting $c = 0.1375$ into equation (6) gives the final working relationship that:

$$y = a.x^{0.1375} \qquad (8)$$

The example of derived "10% graph paper" shown as fig.6 was obtained by substituting a limited number of values for **a** into equation (8) and superimposing the resulting curves onto a conventional orthogonal gridline background. Working examples of "10% graph paper" use a much larger number of values for **a** – say 40 to 60. The paper can either be converted into a transparency or used directly for plotting data points and simulated saturation curve.