ACADEMIC STUDY

Prof. Dr. David Kirk | *Coventry University, U.K.*

Satisfactory Peening Intensity Curves

INTRODUCTION

Obtaining satisfactory peening intensity curves is a basic priority. Such curves will:

1 Allow acceptable derivation of the peening intensity,

2 Help in determining the time required to achieve specified coverage levels and

3 Indicate the stability of the arc height measurements as a function of time.

Achieving these objectives is assisted by knowing the factors that constitute a satisfactory peening intensity curve. The first objective is very well-documented but the other two are often either overlooked or ignored. As an extreme example consider the situation shown in fig.1. This would be universally classed as being an unsatisfactory peening intensity curve. The data set indicated is not impossible. It could have involved a "pre-bow" of 25μm for a measured unpeened strip together with four strips peened using a rapidly-falling air-blast pressure.

A "best-fitting" curve is shown in fig.1. This was obtained by using a curve-finder program – which revealed a type of "rational function" as having the "best fit". This curve is, however, inappropriate as it does not remotely resemble the shape that a peening intensity curve should have if the shot stream is reasonably stable. Attempts to fit this data set to a more familiarly-shaped curve do, however, generally fail.

It is clear that:

Data should be fitted to a suitable type of curve – rather than the other way round.

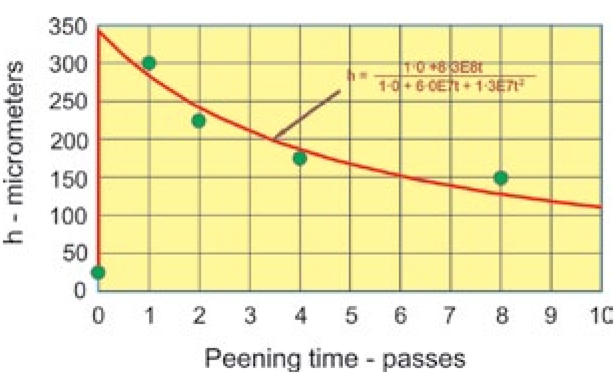

Fig.1 Unsatisfactory Peening Intensity Curve indicating an unstable shot stream.

1 SATISFACTORY DERIVATION OF THE PEENING INTENSITY

Several factors affect whether or not a given peening curve can be classed as "satisfactory" in terms of peening intensity derivation. These include pre-bow, curve shape and choice of curve-fitting program

Pre-Bow

Every Almen strip deviates from flatness to some extent. The most significant deviation is called "pre-bow" which can be measured before any peening is applied. Few, if any, shot peeners would include such measurements on a graph. This does, however, lead to a situation where we can have two different saturation curves produced using the same peened strips. One curve represents "Measured arc heights versus peening time" and the other "Change in arc height versus peening time". The difference is illustrated in fig.2.

The pre-bow of 0.001", used for fig.2, is a pure assumption. It is used to illustrate and quantify the effect of a constant pre-bow (if it had been present). The upper curve has the added assumption that the unpeened specimen's measured arc height has been plotted as being zero (even though it would have been measured as +0.001"). Using Solver EXP2P,

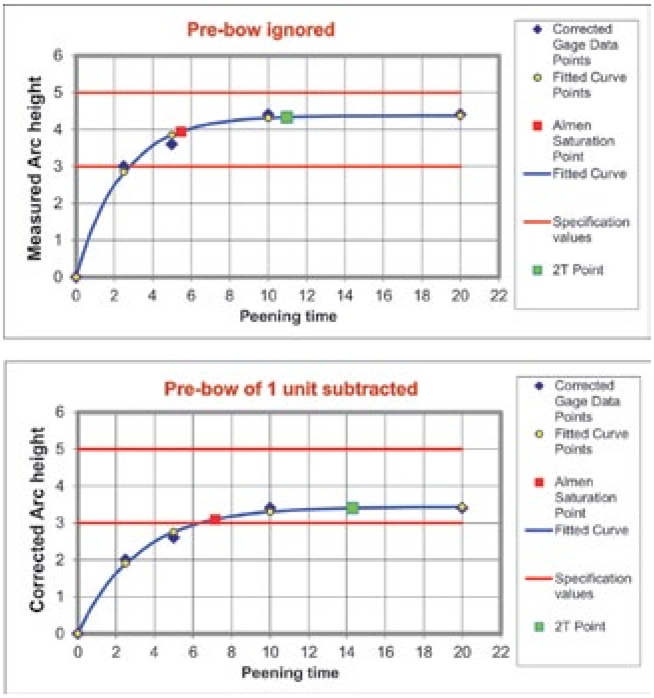

Fig.2 SAE Data set No.2, ignoring and allowing for an assumed constant pre-bow of 0.001".

the upper curve has a derived peening intensity of 3.94 occurring at T = 5.48. This compares with the lower curve's derived values of 3.09 at T = 7.19. Effects of pre-bow can therefore be quantified by using an appropriate peening intensity curve analysis program. J442 specifies a maximum pre-bow of 0.001" for N and A strips and 0.0015" for C strips. This example therefore shows the effect of having a maximum pre-bow. Some specifications, such as the current version of J443, require that any pre-bow be allowed for.

It is generally accepted that every peening intensity curve will pass through the origin (0, 0) of the graph. This general assumption of passing through the origin is useful - it adds an extra point to the number of points that can be employed for estimating the curve's equation.

In practice several strategies are available when faced with the problem of pre-bow:

1 Ignore any pre-bow completely and assume it to be zero.

2 Measure every Almen strip before peening and deduct any detectable pre-bow from subsequent measured arc heights.

3 Use Almen strips for which the pre-bow has been measured and indicated by the manufacturer – again deducting pre-bow from subsequent measured arc heights.

4 Use high-quality Almen strips for which the manufacturer guarantees that the pre-bow will be so small as to be insignificant – therefore assuming it to be zero.

The choice of strategy will depend, to some extent, on the rigors of the peening job involved (low-spec or high-spec) and the attitude adopted by the shot peener.

Satisfactory Shape of Fitted Peening Intensity Curve

Every curve has a corresponding equation that defines its shape. A satisfactory shape (and hence equation) of a peening intensity curve should meet the following criteria:

C1 The curve will pass through the origin of the graph (0,0).

C2 An initial rapid, almost linear, increase in arc height will be followed by a continuous reduction in the rate of increase.

C3 The rate of arc height increase becomes small after considerable peening.

C4 The curve should be capable of yielding the peening intensity values for the sets of data included in J2597 (derived to within the limits prescribed).

A pivotal problem is to decide on an acceptable equation that will represent a satisfactory shape. One approach, used by the French Standards Committee, is to name a single, two-parameter, equation that must be used when working to their specifications. The SAE Sub-Committee on computerized curve fitting has adopted a different approach. This is that any fitting-equation is acceptable provided that it yields derived peening intensity values that lie within prescribed limits of ± 0·001" when applied to its reference data sets, see Table 1.

Table 1
SAE J2597 Data Sets for Peening Intensity Curve Verification

Set 1		Set 2		Set 3		Set 4		Set 5	
Time	Arc height	Time	Arc height	Time	Arc height	Time	Arc height	Time	Arc height
4	0.0060	2.5	0.0030	3	0.0065	1	0.0038	4	0.0062
6	0.0069	5	0.0036	6	0.0081	2	0.0051	6	0.0070
8	0.0070	10	0.0044	12	0.0088	3	0.0052	8	0.0072
12	0.0070	20	0.0044	24	0.0090	4	0.0053	12	0.0072
Intensity	**0.0064**	**Intensity**	**0.0040**	**Intensity**	**0.0080**	**Intensity**	**0.0048**	**Intensity**	**0.0066**

Set 6		Set 7		Set 8		Set 9		Set 10	
Time	Arc height	Time	Arc height	K/Feed	Arc height	K/Feed	Arc height	K/Feed	Arc height
1.1	0.0046	2	0.0055	0.25	0.0081	0.25	0.0108	0.25	0.0045
2.3	0.0087	3	0.0066	0.50	0.0096	0.50	0.0129	0.50	0.0054
4.5	0.0101	4	0.0067	0.75	0.0100	0.75	0.0137	0.75	0.0059
9	0.0107	6	0.0068	1	0.0103	1	0.0144	1	0.0058
Intensity	**0.0098**	**Intensity**	**0.0063**	2	0.0108	2	0.0157	2	0.0062
				4	0.0113		0.0164	4	0.0064
				Intensity	**0.0093**	**Intensity**	**0.0137**	**Intensity**	**0.0054**

These data sets correspond to a wide range of peening conditions. The derived intensity values are the averages of values produced using four different curve-fitting procedures.

Training in the use and selection of a satisfactory equation is provided by the Solver suite of Excel programs available through Electronics Incorporated at www.shotpeener.com/learning/solver.php. This offers a range of equations where user choice is available. A general guide is that:

1 A two-parameter equation should always be used when the data set contains only four points (excluding 0,0).

2 A three-parameter equation offers a better approach to the true shape of a perfect saturation curve but should normally only be used for data sets containing six or more points representing a reasonably stable shot stream. It can also be used for data sets containing five points but with an added proviso. This is that the five-point data set should represent a stable shot stream and therefore be a reasonably good fit to the curve.

Choice of Program for Deriving Peening Intensity Values

Users normally have a variety of programs to choose from, unless working to the French specification. There are a few companies that have their own in-house programs whose use is, presumably, prescribed. Alternatively there are either free programs, such as the Solver Suite, or commercial programs. The Solver Suite has always been intended to be educational – giving users an insight into how curve-fitting is carried out and subsequently analyzed to yield Peening Intensity and T values. It has, however, found extensive commercial application.

An important question is "Do different programs yield different peening intensity values when fed with the same data set?" The answer is "Yes – but the differences are so small as to be insignificant".

The target intensity values in Table 1 were themselves obtained as the averages of four different programs (A to D of Table 2). Table 2 is a compilation of the SAE results together with results obtained using the Solver Suite Programs EXP2P, 2PF and a commercial program shown as "COM 1". All seven programs satisfied the SAE peening intensity criterion for every one of the ten data sets. Seven is just large enough a number to afford statistically-significant standard deviation values – shown as STDEV in Table 2.

The values shown in Table 2 are very encouraging with respect to derivation of peening intensity, generally showing very close agreement for the different programs. The average percentage standard deviation is only 1.78 ("% Dev" being 100*STDEV/Average). It should be noted, however, that all of the ten SAE data sets represent 'good data'.

2 INDICATION OF PEENING INTENSITY TIMES

Another important question is "Do different programs yield the same peening intensity times when fed with the same data set?" The answer is "No – the differences are not large but they are significant".

The time, T, at which any given peening intensity value occurs is an indication of the rate of coverage that could be achieved using the corresponding shot stream. It is, therefore, of some interest to examine the effect of different programs on derived T values. Table 3 on page 30 gives these times for the seven programs shown in Table 2 applied to the ten SAE data sets. It is apparent that there is a much greater fluctuation of intensity times than for the intensity arc heights shown in Table 2. The average percentage standard deviation value again quantifies this difference – 11.27% for T compared with only 1.78% for arc height, H, at T. It can be concluded that different programs predict peening intensity times that can be significantly different from one another.

Table 2
Summary of Peening Intensities derived by applying different programs to SAE Data Sets

Program	Peening Intensities for different SAE Sets - inch x 1000									
	1	2	3	4	5	6	7	8	9	10
A	6.4	4.0	8.0	4.8	6.6	9.8	6.2	9.9	13.5	5.4
B	6.3	4.0	8.0	4.8	6.5	9.7	6.2	9.4	13.7	5.4
C	6.5	4.0	7.9	4.9	6.7	9.8	6.4	9.2	13.9	5.3
D	6.4	4.0	8.0	4.9	6.6	9.9	6.3	9.3	13.7	5.4
EXP2P	6.4	3.9	8.0	4.8	6.6	9.8	6.3	9.6	13.8	5.5
2PF	6.4	4.0	7.9	5.1	6.6	10.7	6.4	9.4	13.7	5.4
COM1	6.4	4.0	8.0	4.8	6.6	9.9	6.2	9.0	12.9	5.2
Average	6.40	3.99	7.97	4.87	6.60	9.94	6.29	9.40	13.60	5.37
STDEV	0.06	0.04	0.05	0.11	0.06	0.34	0.09	0.29	0.33	0.10
% Dev	0.90	0.95	0.61	2.28	0.87	3.43	1.43	3.07	2.44	1.77

Table 3
Summary of Peening Intensity times, T, derived by applying different programs to SAE Data Sets

Program	Derived peening Intensity times, T, for different SAE Sets									
	1	2	3	4	5	6	7	8	9	10
A	4.64	6.73	6.30	1.90	4.80	4.49	2.74	0.44	0.63	0.51
B	4.43	5.92	5.38	1.73	4.50	3.76	2.59	0.42	0.63	0.47
C	5.42	6.64	5.29	1.95	5.27	4.03	3.07	0.39	0.69	0.40
D	4.72	6.70	5.63	1.89	4.70	4.19	2.80	0.44	0.71	0.50
EXP2P	4.75	5.48	5.38	1.81	4.73	3.92	2.76	0.43	0.55	0.46
2PF	4.75	7.05	6.17	2.62	4.71	6.93	3.36	0.47	0.66	0.50
COM1	4.70	6.72	6.21	1.87	4.81	4.42	2.72	0.3	0.45	0.39
Average	4.77	6.46	5.77	1.97	4.79	4.53	2.86	0.42	0.62	0.46
STDEV	0.31	0.55	0.45	0.30	0.24	1.09	0.26	0.05	0.09	0.05
% Dev	6.42	8.55	7.72	15.07	4.92	24.00	9.18	11.69	14.57	10.57

It may be hypothesized that all of the seven programs indicated in Tables 2 and 3 involve two-parameter equations that are exponential to some maximum value. EXP2P and 2PF programs have equations showing the variation of arc height, h, with peening time, t:

EXP2PF **h = a[1 – exp(- b*t)]**

2PF **h = a[t/(1-b*t)].**

These equations both have "a" outside a bracket. The bracket contains the second parameter "b" as a function of the peening time "t". The unique peening intensity arc height, H, and time, T, are derived from the two equations as follows:

EXP2P **H = 9*a/10 @ T = 2.303/b**

2PF **H = 9*a/11 @ T = 4.5*b**

Applying the equations to the SAE Data Set No.2 gives the results illustrated in fig.3. Fitting EXP2P to the four data points yields a = 4.38 and b = 0.42. 2PF yields a = 4.86 and b = 1.57. Substituting these values predicts that for EXP2P: H = 3.94 at T = 5.48 and for 2PF: H = 3.98 at T = 7.05. The difference in peening intensity predictions (0.04 thousandths of an inch) is tiny when compared with the difference in T-value predictions (1.57).

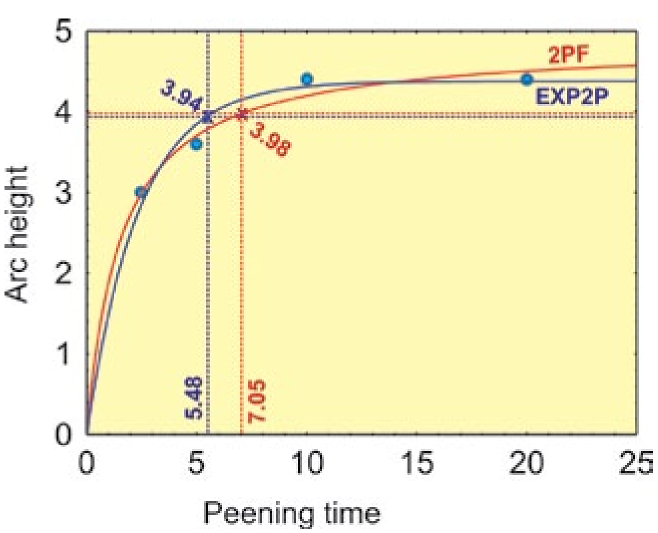

Fig.3 Two different programs applied to SAE Data Set No.2

Special Cases

The current version of J443 allows for "Special Cases". These are declared to be those when a single pass imposes such intensive coverage that it exceeds a corresponding T value. Fig.4 shows the idealized graph and 'virtual' data points that demonstrate a "Type II Saturation Curve". This is unsatisfactory insofar as the 'unique point' at one pass depends on the particular data and the time, T, is vague.

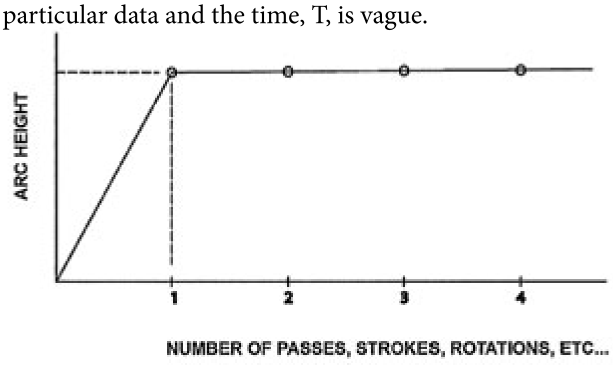

Fig.4 Type II Saturation Curve for Special Cases

A conventional shape of saturation curve could, however, be generated for Special Case situations. This would necessitate modification of the J442 strip holder requirements. Possible modifications range from simple to complex. One simple modification would involve a set of hardened steel masks with holes drilled to different area percentages. Different masks would expose the strip to different percentages of the shot stream. A complex modification would involve a motorized strip holder with variable movement speeds triggered by an incoming shot stream. The movement speeds, in the opposite direction to that of the shot stream, could be percentages of the shot stream travel speed. This would reduce the exposure time to fractions of the stream speed. With either modification a given strip's exposure could be reduced by controlled amounts.

3 STABILITY OF THE ARC HEIGHT MEASUREMENTS AS A FUNCTION OF TIME

The stability of arc height measurements can be quantified using a "Goodness of Fit" analysis. "Goodness of fit" is simply a measure of how closely data points are to a given fitted equation. If every data point lies exactly on the curve then we have a perfect fit. In practice there are always some deviations from the curve. These deviations are termed "residuals" and are the numerical difference between the data point value and the corresponding curve value. If, for example, the arc height measurement is 10.8 and the corresponding value on the fitted curve is 10.881 then the "residual" is 0.081. Table 4 is an extract from the worksheet of Solver Suite Program 2PF applied to SAE Data Set No.8. The data point values in the "Corrected" column have been highlighted to show the distribution of positive and negative residuals.

Table 4
Extract showing distribution of Residuals arising from curve fitting 2PF

Time	Arc Height	Pre-bow	Corrected	Calc. Y	Residuals
0	0	0	0	0	0
0.25	8.1	0	8.1	8.10238	0.0023759
0.5	9.6	0	9.6	9.49129	-0.108713
0.75	10	0	10	10.0665	0.0664861
1	10.3	0	10.3	10.381	0.081047
2	10.8	0	10.8	10.8916	0.0915615
4	11.3	0	11.3	11.1661	-0.133877

The commonest parameter used for estimating all data point/curve deviation situations is called "R-Square". This very powerful parameter is defined as:

R-Square = 1 – SSE/SST

where **SSE** is the **Sum of Squares due to Error**

and **SST** is the **Sum of Squares Total**

SSE appears as "**SUM**" in all of the Solver Suite of programs. It is simply the sum of the squares of the residuals' values. For the example shown in Table 4 "**SUM**" = 0.04912. **SST** is again a sum of squared values. Each value is that of the difference between the measured value and the average of the measured values. For example the average of the six corrected values in Table 4 is 10.02 so that the first squared value is $(8.1 – 10.02)^2$. Adding up the six squared values gives **SST** = 6.1884. R-Square is therefore given by:

1 – 0.04912/6.1884 so that **R-Square = 0.9921**.

0.9921 is more than 99% of the possible maximum value for R-Square (which is 1.0000). Hence we can say, quantitatively and objectively, that the 'Goodness of Fit' is 0.9921.

The requisite calculations for SST and R-Square were made automatically - using a simple modification to the corresponding Solver Suite program – illustrated by the pasted extract shown as Table 5. Calculated values of R-Square can also be compared automatically with a fixed minimum allowable value. If the set minimum value is not achieved then a "Warning" can be flagged-up automatically.

Table 5
R-Square calculation using the same Data Set as for Table 4

-1.91667	3.673611
-0.41667	0.173611
-0.01667	0.000278
0.283333	0.080278
0.783333	0.613611
1.283333	1.646944
SSE	0.04912
SST	6.188333
R-Square	0.992062

CONCLUSIONS

The production of computer-generated peening intensity curves is rapidly becoming standard practice. Increasing awareness of computer techniques will encourage a more detailed knowledge and understanding of the possibilities that computer programs can offer. That is certainly true when it comes to deciding whether or not a satisfactory peening intensity curve has been generated for a particular data set. Some of the factors that define 'satisfactory' have been discussed in this article. With a satisfactory peening intensity curve the three main uses (acceptable intensity derivation, help in determining time required to achieve specified coverage levels and indication of stability of arc height measurements) can be employed.

Visual examination for factors such as goodness of fit can be employed but that is a very subjective process. Objective quantification, based on computerized curve analysis, is a characteristic feature of the factors discussed in this article.