User's Instruction Manual

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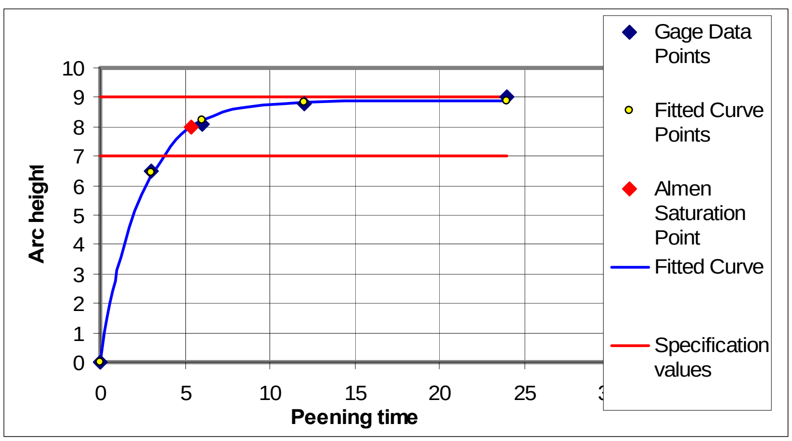

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Saturation Curve Solver

IM:0097 Revision: Release 09 Date: June 2009

SATURATION CURVE SOLVER SUITE
Version 09 for use with Excel 2007
Notes for Guidance

INTRODUCTION

Welcome to ‘Saturation Curve Solving’. These notes are intended to guide readers through the several steps involved in using these curve fitting programs. No prior knowledge is needed, only a basic familiarity with ‘Excel’. This version of the programs require that users have Microsoft Excel 2007 installed.

There are twelve Excel programs in the suite – summarized in Table 1 on the next page. The previous set of six programs was expanded (by popular demand) to include six programs appropriate for 'flapper peening'. Don't be put off by the number of programs! In practice, most users will only use the one or two that best suit their requirements. The flow sheet on page 3 is a guide to the selection of the most appropriate programs and is explained later - in the 'Program selection' section.

All twelve programs are presented as separate Excel 'templates' (Excel 2007 template files have an 'xltx' extension). They are 'open source' programs in which all of the workings can be viewed. For example, dragging aside the graph which appears on each Sheet 1 will reveal the method used to present a smooth curve. Highlighting any cell will show how the contents were obtained. When a program is used and then closed the template asks if you wish to "save". The recommended procedure is to save the work separately as a "worksheet" (Excel 2007 worksheet files have an 'xlsx' extension) – thus preserving the template unaltered for future use.

Each template has three sheets. The first is a ‘working sheet’, the second displays a copy of the final curve (and has space for adding user-orientated information) and the third sheet is a set of ‘test data’ provided by the SAE sub-committee on Almen curve fitting.

Features of the Saturation Curve Solver suite are summarized as follows :

1 Pre-bow correction. A facility is provided for pre-bow measurements to be included. Values entered in the pre-bow column will be automatically subtracted from peened arc height values. If no pre-bow values are entered the program will just use the peened arc height values.
2 Comparator programs. "Comparator" programs have the added feature of being able to superimpose another curve on a chart - for comparison purposes.
3 Flapper correction programs. Measured arc heights produced using flapper peening should be corrected to yield the equivalent of 'standard' arc heights. Two correction procedures are currently used by industry. These are the "Boeing correction" and the "3M correction". Boeing correction requires that each arc height is multiplied by 0.77. 3M correction is based on a well-established correction chart. Both correction procedures are incorporated into corresponding programs within the suite. Measured arc heights (minus any pre-bow) are automatically corrected.
4 Warnings. The range of strip peening 'times' <u>should</u> extend from less than the saturation point time, T, to more than 2T. Warnings are automatically displayed if either, or both, of these requirements are not met. If there are only four data points in each set then only two-parameter programs are recommended.
5 Start values. The required start values are automatically indicated under the 'parameter box'.
6 Data size recommendation. If a three-parameter equation program is being applied to a data set with only four points then a 'recommendation' appears suggesting that a two-parameter equation be used.

Table 1. Summary of Saturation Curve Solver Suite Programs.

SATURATION CURVE SOLVER PROGRAM SUITE

Program Type	Equation	Program No.	File Name
Standard	EXP2P	1	SCS1 S EXP2P vers.09.xltx
	2PF	2	SCS2 S 2PF vers.09.xltx
	EXP3P	3	SCS3 S EXP3P vers.09.xltx
Comparator	EXP2P	4	SCS4 C EXP2P vers.09.xltx
	2PF	5	SCS5 C 2PF vers.09.xltx
	EXP3P	6	SCS6 C EXP3P vers.09.xltx
Flapper - 3M	EXP2P	7	SCS7 FL3M EXP2P vers.09.xltx
	2PF	8	SCS8 FL3M 2PF vers.09.xltx
	EXP3P	9	SCS9 FL3M EXP3P vers.09.xltx
Flapper - BG	EXP2P	10	SCS10 FLBG EXP2P vers.09.xltx
	2PF	11	SCS11 FLBG 2PF vers.09.xltx
	EXP3P	12	SCS12 FLBG EXP3P vers.09.xltx

NOTES:

Program Type: "Standard" and "Comparator" programs are for normal peening operations. "Comparator" programs have the added feature of being able to superimpose another curve on a chart - for comparison purposes. "Flapper" programs allow for the automatic correction of flapper-wheeled strip heights according to either "3M" or "Boeing" procedures.

Equation: "EXP2P" is a two-parameter exponential equation, "2PF" is the French Specification two-parameter equation and "EXP3P" is a three-parameter exponential equation.

File Name: "SCS" is for Saturation Curve Solver, followed by the program number, program type and equation. "vers.09" identifies a specific version of a given program. This will change as new versions are produced. "xltx" is the 'file extension' which identifies the program as being an Excel 2007 'template'. When a template is closed you are asked if you wish to "save". The usual procedure is to then save work as a "worksheet" with an 'xlsx' extension - thus preserving the template unaltered for future use.

Newcomers to computer-based saturation curve solving are recommended to proceed to the next section – a "step-by-step starter guide". Experienced users – especially those who have used earlier versions of the suite – may prefer to skip that section.

STEP-BY-STEP STARTER GUIDE

It is suggested that new users start with **PROGRAM No.1.** This uses a two-parameter (**a** and **b**) exponential equation. After getting familiarity with that program you should then progress to becoming familiar with the other programs. The following is a 'step-by-step' guide for new users.

1 - LOAD TEMPLATE SCS1 S EXP2P vers.09.xltx

On loading, **SCS1 S EXP2P vers.09.xltx** should open at Sheet 1. If it doesn't, click Sheet 1 at the bottom of the open page. Do not be put off by what seems to be a mass of numbers – all will become clear! The sheet contains a previous use of the template. Take a while to become familiar with the layout of Sheet 1.

The blue-bordered box spanning columns B, C and D is where you put your data. Up to 9 points can be accommodated. Just above the blue box is the assumed 'extra data point' of 0,0. That is there because we can assume that our curve must pass through zero (no deflection because of no peening time). The previous answer for saturation intensity is in box **J8.**

2 – ENTER DATA

First clear the existing data from the **B/D** blue box ('Highlight' and 'Delete'). You will see that other numbers on the sheet change automatically. Don't worry about it! Then **enter your set of data points – including pre-bow values, if any**. The data must be entered as either 'thousandths of an inch' or microns. For example: use "12" instead of "0.012" or "5.4" instead of "0.0054"(mm). That is because the program involves the squares of tiny differences and Excel cannot cope here with very small quantities.

Enter, if you wish to, the **Lower and Upper specification limits** in the red frame in column **E**. Otherwise, delete the two pre-existing values from the frame.

3 – EXAMINE SHEET 1

When you entered the last data point in your set and confirmed it by pressing the 'green tick mark' the data set will have been fitted to the **two-exponent exponential** equation using the previous user's values for **a** and **b**. This will normally be a bad fit. The bad fit should be obvious on examining the plotted graph on Sheet 1. You now need to obtain the **best** values for **a** and **b** for the data set that you have just entered.

4 – ENTER 'START VALUE' FOR a INTO J4

The largest arc height value in your data set should now be entered into box **J4**. Excel 'Solver will use that value as a starting point for its calculations that yield the 'best-fitting' values of **a** and **b**. This 'start value' is automatically shown in cell **J6**.

5 – USE 'SOLVER' TO CALCULATE BEST VALUES FOR a and b.

Click on the "**SUM**" value that is in box **H16.** Now click on **'Data'** and then on **'Solver'** (in the top toolbar). **(If 'Solver' doesn't appear on clicking 'Data' then install it as follows: click the 'Office button' (top left), click 'Excel options' and then click 'Add-ins', select 'Solver add-in' and click 'OK'. Then you can use 'Solver').** A 'Solver Parameters' box appears. Just click **'Solve'** in the top right-hand corner. Excel has now been told to minimise the 'SUM' by changing the values of **a** and **b** in **J4** and **J5**, time after time after time. Having done its very best, the value in the SUM box will be the smallest value that it can find. Another box now appears of 'Solver results'. Make sure that the first sentence is that "**Solver found a solution**". (If it cannot find a solution there is something wrong with the data!). Then **press OK**.

6 – EXAMINE AND SAVE RESULTS

The required Saturation Intensity Height is given in box **J8**. The corresponding time is given in box **J9**. A graph containing the saturation curve, data points, and Almen Saturation Point is given on both Sheets 1 and 2. If you have entered (or not removed) Lower and Upper specification values in E16/17, the graph will also display two red, horizontal, lines. Check that the graphed results appear to be reasonable e.g. that the 'red square' indicating the Saturation Point lies on the blue curve and that the curve is smooth. If the graph appears to be unreasonable, clear your data, cut-and-paste one of the examples from Sheet 3 and follow the procedure again. You should now get the same values as are given in Sheet 3. Then re-enter your own data and repeat the preceding steps. If you have entered Lower and Upper specification values in E16/17 you should check to see if the Almen Saturation Point lies between the specification limits.

Save your work as a separate Excel workbook (i.e. with an xlsx extension) before closing the template. This simply involves clicking on the 'Office button' (top left), highlighting 'Save as' and then clicking on the first option of the list that appears. Then choose an appropriate file name and click 'OK'.

On closing down a template you will be asked if you wish to save alterations. Tick "**No**" (to preserve template unaltered) or "**YES**" (to change details of template).

7 – DETAILS

Each program is written in plain Excel and nothing is completely 'hidden'. Some 'don't need to know' workings are covered by the graph on Sheet 1. These workings are simply to help Excel produce a smooth curve and to know to draw horizontal lines for the specification limits. Highlighting any given cell reveals the working details. For example, Column F contains the worked-out values for points that lie exactly on the equation (the yellow points on the graph). Column G contains the differences (called "**Residuals**") between the arc heights of column F and those of column E. Column H contains the squares of the column G values. It is the **sum** of the column G values that 'Solver' has to minimise – hence producing the required "**least-squares**" curve with parameters **a** and **b**.

Note that in column G the values **must** be a **mixture of positive and negative numbers**. That is the computer equivalent of drawing a curve manually that passes **between** data points. The actual mixture of numbers depends upon the number of data points. If you have only four data points then there are only three possibilities: (1) two points with positive differences and two with negative differences, (2) three points with positive differences and one with a negative difference and (3) three points with negative differences and one with a positive difference. The occurrence of all three possibilities (with different data sets) represents normal scatter of real data.

8 – PRACTICE SESSION

New users are recommended to spend the few minutes needed in a single session to try the ten data sets given in Sheet 3. Start by clearing the 'Specification Box' – because none of the Sheet 3 examples have required upper and lower limits. Then proceed with each example in turn - to build confidence and speed in program usage. The values derived for the data sets were obtained by using Program 1.

PROGRAM SELECTION

The selection of an appropriate Solver program depends upon four factors:

1 **The number of points in your data set,**
2 **Equation preference/specification,**
3 **Type of peening ('Standard' or 'Flapper')** and
4 **Need for cross-referencing.**

1 Number of points in data set.

The **ABSOLUTE MINIMUM** of data points in a set is **FOUR**. With only four points in a data set then <u>only</u> the two two-parameter equations (**EXP2P** and **2PF**) are recommended. The four points must be 'normally distributed' (relative to the curve) in order to get a reasonable approach to the true shape of an Almen Saturation Curve. That means that we must rely entirely on the veracity of all four data points. If any one of the data points is so dubious that it has to be rejected then our curve-fitting becomes <u>interpolation</u> (curve must then pass through all three remaining data points).

With five points or more in a data set there is a choice of three equations (**EXP2P, 2PF** and **EXP3P**).The three-parameter **EXP3P** is normally recommended. One exception to that would be if a given organisation produces a mixture of four-point and five-or-more-point data sets. For the sake of consistency it might then be preferable to use just a two-parameter equation. Five points allows one dubious data point to be omitted and still permits regression curve-fitting of a two-parameter equation.

The use of the three-parameter equation programs is very similar to that for the two-parameter programs - so far as establishing the equation parameters is concerned. There is, however, a difference when it comes to determining the corresponding Almen Saturation Point. For the two-parameter equations the Almen Saturation Point is calculated automatically. That is possible because the "10 per cent criterion" is a very simple function of two-parameter equation parameters. With the three-parameter equation, however, we have to use Excel's **Goal Seek** function to satisfy the "10 per cent criterion". The instructions are given on Sheet 1 of the corresponding programs.

2 Equation preference/specification.

The two equations (**EXP2P** and **2PF**) will yield very similar results for Saturation Intensity when applied to a four-point data set. This can be verified by comparing the Sheet 3 results using the two equations. The **2PF** equation is the required equation when working to the French specification **NF L 06-832** (December 1998). If 2PF is not specified then it becomes a matter of individual preference. EXP2P is the simplest of the family EXP2P, EXP3P and EXP4P* (* EXP4P is available on special request but is normally only of research interest).
Perhaps the most important tenet of saturation curve fitting is that "Points should be fitted to a known curve". There is a seductive temptation to "Find a curve that best fits our points" – which is the wrong approach and must be always be resisted. The correct approach is to select a particular program and let the computer find the best-fitting parameters of the corresponding equation.

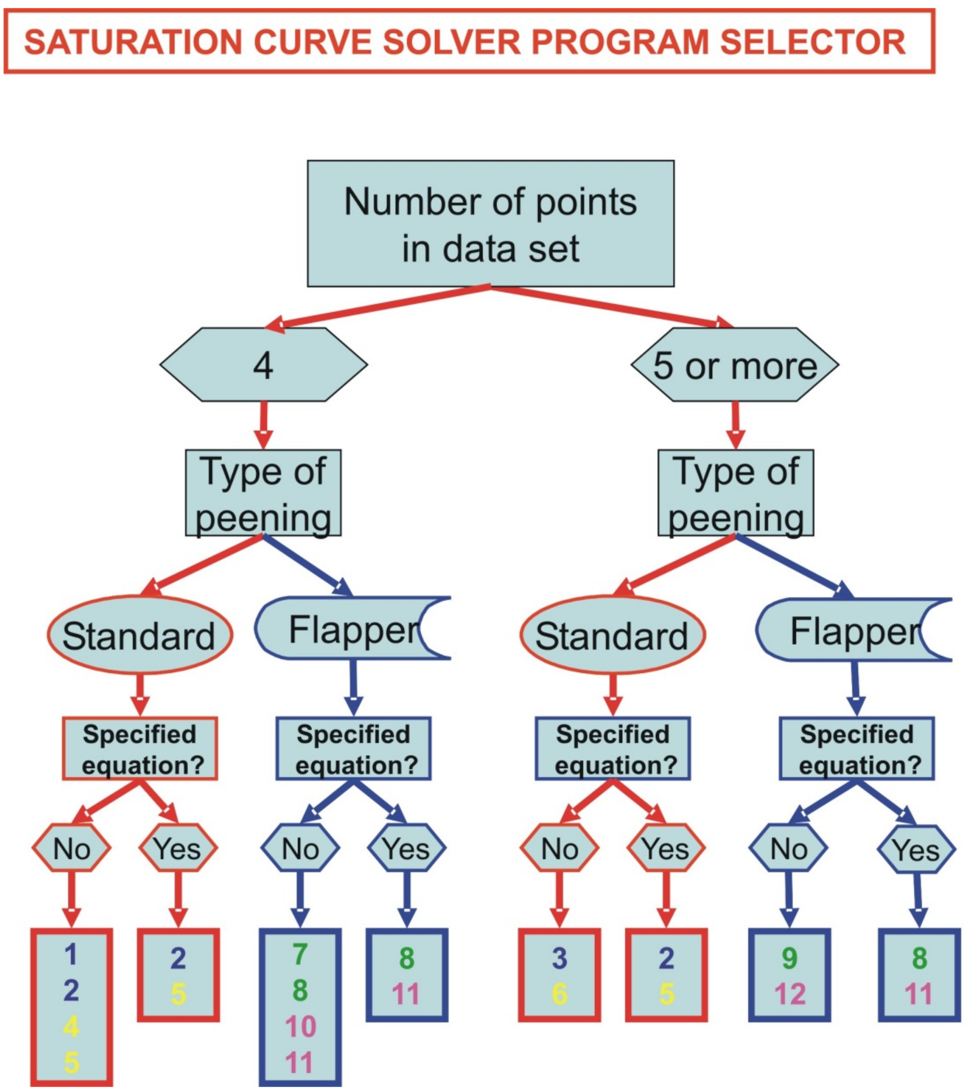
3 Type of peening ('Standard' or 'Flapper').

Flapper peening has become a well-established, but minority, process in the range of shot peening procedures. The Almen strip fixture is different from that for 'standard' peening insofar as the strip is held magnetically, rather than clamped mechanically, during peening. As a consequence the measured arc heights tend to exaggerate the peening intensity. In order to compensate for that exaggeration two different correction procedures are currently specified. These are those originating from the '3M' and Boeing companies. The 3M correction is more complex than the simple "multiply by 0.77" Boeing correction. Three programs are available in this suite for each of the two correction procedures.

4 Need for cross-referencing.

Users with a wealth of stored saturation curves may wish to compare curves on the same graph. One example is the situation where nominally-identical peening parameters have been applied but have yielded significantly-different saturation curves. The sub-set of 'Comparator' programs allows two curves to appear on the same graph. The equation parameters from the reference curve are added on Sheet 2 to activate this facility.

Selection from the combined multiplicity of choices is summarised in the flow chart presented on page **7.**



Recommended programs are shown numbered in the bottom row of boxes. "Specified equation?" relates to whether or not the French-specified fitting equation MUST be used. After "Type of peening" the red routes relate to standard peening and the blue routes to flapper peening program selection.

APPENDIX

VARIABILITY OF DATA POINTS

All measurements have an associated variability. The most familiar parameter is probably the 'standard deviation of a normally distributed variable'. A less familiar, but arguably more useful, variability parameter is the **variance,** which is simply the square of the standard deviation, **σ**. The advantage of using variance is that the total variability is simply the sum of the variability of each contributory factor. The total variability of Almen data point measurements, σ^2_T, is made up of the separate variabilities of the strips, measurements and applied peening. Hence we have that:

$$\sigma^2_T = \sigma^2_S + \sigma^2_M + \sigma^2_{AP} \qquad (1)$$

where the S, M and AP subscripts refer to strip, measurement and applied peening respectively. Almen strips are produced to very close tolerances so that the σ^2_S contribution will be very small. The σ^2_M contribution depends upon the quality of the Almen gage and the operator's skill/assiduousness. It can be measured easily by carrying out repeat measurements on the same curved strip and calibration block. With careful attention to detail, σ^2_M will also be relatively small. The major factor contributing to variability will normally be σ^2_{AP}. During actual shot peening there will always be some variation of the parameters that affect strip deflection. Carrying out repeat measurements, for nominally identical peening parameters, can be used to monitor this variability.

The main reasons for the previous statements are to emphasise (a) that we cannot expect to regularly produce data sets that will lie <u>precisely</u> on a given shape of equation and (b) that we must be vigilant in our production of data sets.

The **RMS-R** value in box **J16** can be used as a direct measure of the variability of the data relative to the smooth equation curve. When a routine has been set up in a given organisation an average of the RMS-R values can be accumulated for comparison/control purposes. Note that the value will be greater, on average, the larger is the Almen intensity (simply because the numbers are larger).

Dr Kirk joined Coventry University as a Senior Lecturer in Metallurgy in 1960 and rose to become Chairman of the School of Materials. His research interests at Coventry University initially centered on the measurement of residual stresses in industrial components using X-ray diffractometry. Interest in residual stresses led to research into shot peening and the setting up of the Shot Peening Research Laboratory at Coventry University. He set up Coventry Science Consultants Ltd. and was chairman until he closed the business shortly before his retirement from Coventry University in 1998. He was Chairman of the Fifth International Conference on Shot Peening held at Oxford University in 1993, where he was elected as Chairman of the International Scientific Committee on Shot Peening. In 1996 he received their "Lifetime Achievement Award". On his retirement, Dr. Kirk became an Honorary Research Fellow at Coventry University and is now Visiting Professor in Materials in their Faculty of Engineering and Computing. He is a featured contributor to The Shot Peener. .

SATURATION CURVE SOLVER EQUATIONS

Three different equations are used for the suite of programs. These are designated as:

EXP2P, 2PF and EXP3P.

1 **EXP2P** This is a two-parameter exponential equation:

h = a(1- exp(-b*t)

where **h** is Almen arc height, **t** is corresponding peening time and **a** and **b** are the two parameters.

2 **2PF** This is a two-parameter 'saturation growth' equation:

h = a*t/(b + t)

where again **h** is Almen arc height, **t** is corresponding peening time and **a** and **b** are the two parameters.

The French Specification NFL 06-832 requires that this equation is used.

3 **EXP3P** This is a three-parameter exponential equation:

h = a(1- exp(-b*t^c))

where **h** is Almen arc height, **t** is corresponding peening time and **a**, **b** and **c** are the three parameters.

All programs use the 'Method of Least Squares' to minimise the differences between data points and fitted equation points.

A paper on the accuracy of Almen curve fitting appears in the Winter 2006 edition of The Shot Peener. That paper includes a discussion of the pros and cons of using different equations and different data set sizes.

TROUBLESHOOTING

A large number of shotpeeners have been converted to the merits of computerized saturation curve analysis by using the Saturation Curve Solver Suite. Tens of thousands of data sets have now been analyzed with remarkably few problems being experienced. Those problems have invariably been found to involve one or other of the following:

1 Peening heights entered as "inch" rather than "thousandths of an inch".

Excel, although very powerful, is not a dedicated curve-fitting program. This means that it is not happy when it has to deal with the squares of very small numbers e.g. 0·0001 squared is only 0·0000001. The pragmatic solution is to always enter 'English' arc heights as thousandths of an inch and 'Metric' arc heights as micrometers. Hence, for example, 0·0001" is entered as 0·1, 0·0014" as 1·4 and so on. The routine use of 'thousandths/micrometers' has the added advantage that specification limits are generally quoted in those units.

2 Wrong choice of equation.

There is always a temptation to use an equation that contains too many parameters – on the grounds that "it looks better because it is a better fit". This temptation must be avoided! One user had problems trying to apply the three-exponent program EXP3P to data sets comprising only four points. With only four points in a data set always use a two-parameter program.

3 Program corruption.

The programs are supplied as 'templates' (which have an .xltx extension) so that if changes are made during use and then 'saved as template' those changes become embodied in the program. Such changes, if accidental, amount to corruption. Work should always be saved separately as an Excel workbook. On closing a program Excel asks the user if the work is to be saved and automatically offers as first choice an Excel 'Workbook' (which has an .xlsx extension).

4 Faulty data sets.

The individual data points making up a given set **should** satisfy two requirements: (1) be a reasonably-good fit to one or other of the appropriate equations and (2) be properly distributed relative to the saturation point.

Help.

Free help is available from the author, via prof.david.kirk@btinternet.com, if problems are encountered. All discussions will be treated in strictest confidence.