Saturation Curve Analysis and Quality Control

by David Kirk

INTRODUCTION

Users specify the range of indentation ability of the shot streams to be used on their components. They are able to do this by virtue of the so-called "Saturation Intensity" which is a quantitative measure of shot stream indentation ability. The range is normally specified as upper and lower limits for the saturation intensity, which has to be obtained from a saturation curve. At various stages in shot peening we need to confirm that the specified indentation ability is being employed. These stages include the initial set-up of a job and subsequent verification intervals. The primary quality control application of saturation curve analysis is, therefore, the determination of saturation intensity values. A secondary application is to obtain an indication of the Almen strip indentation rate.

SATURATION CURVE SHAPE

Each shot particle that indents the surface of an Almen strip causes a minute plastic expansion of that surface. This expansion induces a corresponding tiny increment of convex curvature into the strip. Because a peened strip has received a very large number of indenting particles we get a measurable curvature – expressed as the deviation from original flatness and termed "Almen Arc Height". On initial exposure to a constant shot stream each shot particle can impose a similar increment of curvature. As a consequence the Almen arc height initially increases almost linearly with peening time. With further peening, the strip surface progressively work hardens so that the tiny increment of curvature attributable to each indenting particle is reduced. The rate of Almen height increase must therefore slow down. Eventually the incremental contributions become negligible. The slowing down and subsequent leveling-out are the reasons for the characteristic shape of Almen saturation curves.

Shot streams with different indenting ability will give different 'saturation curves'. With increase in shot velocity (and therefore of indenting ability) there is a corresponding increase in curve height, see fig.1. We should also note that the greater the shot flow the quicker will be the increase in arc height. That means that we can have different saturation curves without any difference in indentation ability.

Consider next the problem: "How can we assign to each saturation curve a quantity that uniquely defines the indenting ability expressed by that curve?" To solve that problem we need to find a particular point of the curve that <u>defines</u> the curve. The standard solution is the so-called "ten percent rule". This solution gives us: **"The (first) point on the curve for which doubling the peening time increases the arc height by 10%"**. For every saturation curve there is only one such point – shown as dots in fig.1. It should be emphasized that **the saturation point is not a data point**, it is a **derived point**. The saturation intensity is a defined high-curvature point of the saturation curve. There are alternative 'characteristic points'. Mathematically-minded readers will note that the curve's curvature at the 'saturation point' is close to the 'point of maximum curvature'. If we know the mathematical equation for the curve we can derive the point of maximum curvature by solving a relationship that includes the first and second derivatives of the curve's equation.

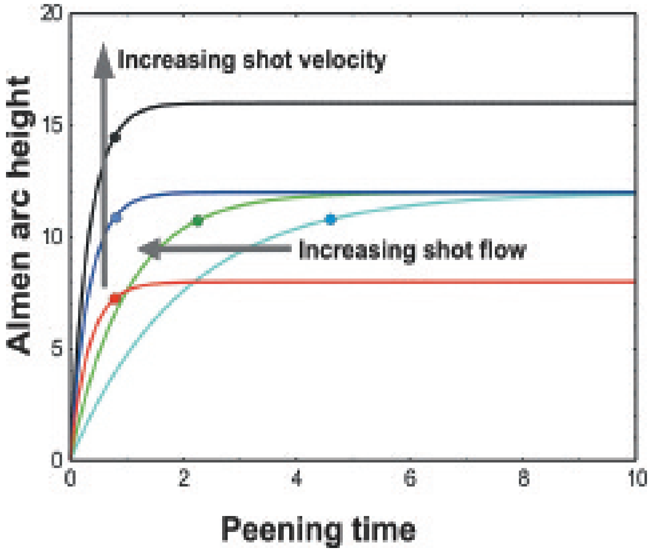


Fig.1 Effects of shot velocity and flow rate on position of 'saturation point'.

There are various specifications that detail the requirements for saturation curve measurements. All of these specify that several Almen strips must be exposed for different times to the same shot stream. The measured arc heights are then plotted against peening time. A curve must then be drawn so that the saturation intensity can be estimated. There are two alternatives: manual curve fitting and computer-based curve fitting. With the universal availability of computers and appropriate curve-fitting procedures the former technique should be 'consigned to history'.

SATURATION CURVE PREDICTION

One advantage of computerized curve-fitting is that the curve's equation has parameters that are directly related to saturation intensity and saturation time. Popular equations used for curve-fitting are 'two-parameter exponential' and 'two-parameter saturation growth'. These are:

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

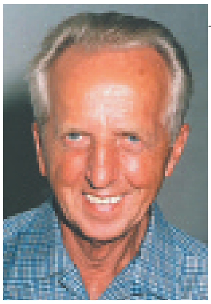
and

$$\mathbf{h = a*t/(b + t)} \qquad (2)$$

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

For both equations the saturation intensity is a fixed proportion of parameter **a**, **[9a/10** for equation (1) and **9a/11** for equation **(2)]**. Similarly the saturation time is a fixed proportion of parameter **b**, **[2·303/b** for equation (1) and **4·5*b** for equation (2)]. Fig.2

Continued on page 26



Dr. David Kirk, our "Shot Peening Academic", is a regular contributor to The Shot Peener. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University, U.K. and is now a member of their Faculty of Engineering and Computing. We greatly appreciate his contribution to our publication.

Continued from page 24

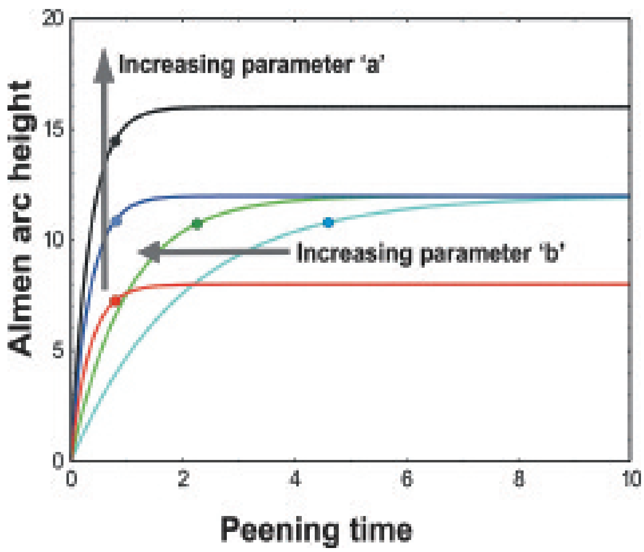


Fig.2 Effect of arc height and peening time on two-parameter exponential saturation curves.

illustrates these relationships for equation (1). The similarity with fig.1 is not coincidental!

The machine control settings that lead to every saturation curve produced by a particular peening shop should have been documented. Settings for a new job can therefore be based either directly on past records or on the superintendent's wealth of experience (or both). Armed with a knowledge of the equation parameters we can plot an expected saturation curve immediately. The case study shown in the next column illustrates the approach used by the author for his laboratory peening facility.

The primary factors that govern saturation curves, for a given shot charge, are shot velocity and shot stream flux. In this context, 'flux' is the number of shot particles crossing each unit area of the shot stream's cross-section. Shot velocity is controlled by varying either air pressure or wheel speed. Shot stream flux is varied by means of some type of feed valve – such as a Magnavalve. There is, however, an inter-dependence of shot velocity and shot flux. That means that we cannot vary velocity and flux independently. There are several factors that contribute to the inter-dependence. The major factor is the efficiency of energy conversion. For an air-blast machine the compressed air is providing kinetic energy, some of which is translated into kinetic energy of the shot particles. The greater the shot flux, the lower is the air stream's efficiency in accelerating the shot particles. Complex physics are involved!

DATA POINT SELECTION

Data point selection for a saturation curve is very important, but is rarely mentioned in specifications. The primary objective is to determine the characteristic 'saturation point' to within reasonable confidence limits. It follows that the range of selected data points should straddle the expected saturation point without being too close together. This means that we should have some points at lower times than the saturation time and some at longer times. The most useful sequence of peening 'times' is generally found to be based on a 'geometric progression'. For example, the sequence of numbers 1, 2, 4, 8, 16 and 32 is a geometric progression where

Case Study: Attempt to produce an Almen Arc height of 0.015" using S110 steel shot.

The author's records are stored as Excel spreadsheets with separate sheets for each type and size of shot. For each shot type there are separate columns for air pressure, shot feed rate (with actual MagnaValve settings), gun-to-component distance, gun type (suction fed or direct fed), angle of impact, Almen strip type, test date, arc heights and times, saturation intensity, saturation time and fitted curve parameters. Complementary sheets detail the history of each shot charge in terms of origin, purchase date, sieve details, image analysis, etc. With only about a thousand saturation curves on record it was a simple task to use Excel's Data/Sort facility to highlight the several previous combinations of settings that yielded approximately 0.015" when using S110 steel shot. The recorded saturation curve parameter values were then fed into a Curve Solver computer program to produce a "reference curve". The combination of machine settings that gave that "reference curve" were then used to produce a new, current, saturation curve. This new curve was then plotted on the same graph as the reference curve. Fig.3 shows the outcome.

Current Curve

a	b	Sat.Int.	T
15.31	0.43	13.78	5.32

Reference Curve

a	b	Sat.Int.	T
16.49	0.32	14.84	7.20

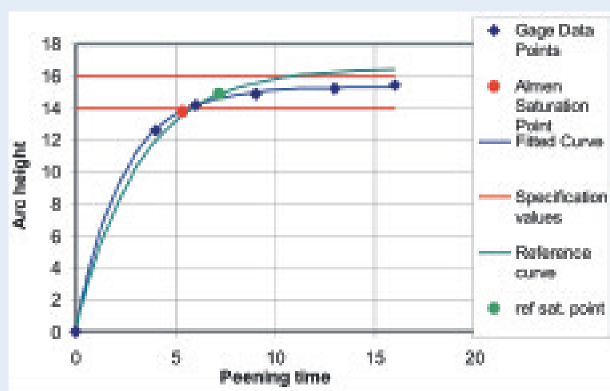


Fig.3. Comparison of reference and new saturation curves using Curve Solver 2EXP v3.00C.

For the situation represented in fig.3 there is a clear discrepancy between the two curves. The machine settings have produced a lower saturation intensity and shorter saturation time than was expected. By cross-checking with the complementary data it was found that the S110 shot charge had been in use for so long that its average diameter was substantially lower than when the reference curve was produced. That led to a lower intensity potential and a faster coverage rate. The problem was subsequently solved by clearing out the shot charge and replacing it with new shot.

Continued on page 28

Continued from page 26

each number is double the preceding number. Such a sequence normally allows an efficient utilization of the limited number of data points.

Fig.4 illustrates a real situation where the choice of data points was not efficient. This situation occurred because a high shot stream flux was imposing a very high coverage in a single pass over the Almen strips. Computer-based curve-fitting yielded the indicated T and 2T arc heights. Typical error bars are shown for the four data points. It takes little imagination to appreciate that, given the error limits shown, the 'real' T value is anywhere between 0·1 and 1·0 strokes. We cannot, however, select fractions of a peening stroke! Stroke speeds can often be increased to yield the equivalent of stroke fractions. With fig.4, half and quarter stroke fractions would be far more effective than the three and four stroke points. It would be simplistic to argue that the shot feed rate should be reduced so that the saturation time becomes much longer. Shot feed rate reduction would mean that production rates would suffer badly.

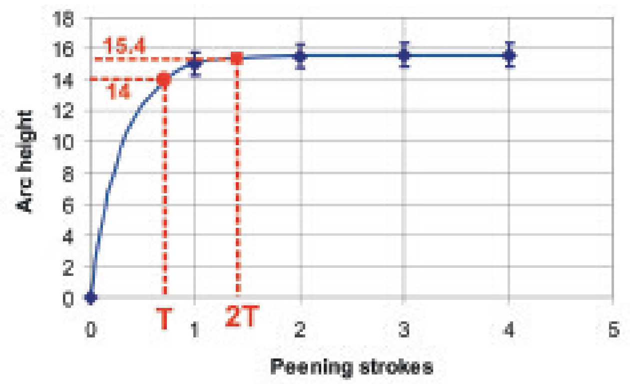


Fig.4 Almen saturation curve with data points beyond the saturation point.

COVERAGE

Saturation times are a useful guide to the rate at which components will receive specified coverage levels. For any given machine set-up, the coverage rate of the Almen strips is inversely proportional to the saturation time. Hence, the shorter the saturation time the higher will be the coverage rate. The coverage rate for a component will not be the same as that for Almen strips. That is because there is normally a difference between the indentation resistance (hardness) of the component and that of the Almen strip. The coverage rate for a component is therefore inversely proportional to both saturation time and component hardness. If the component is softer than the Almen strips then it will receive a higher coverage rate than will the strips. Conversely, if the component is harder than the Almen strip then the component's coverage rate will be lower than that for the strips.

T-TESTING

T-testing is an important feature of quality control. The objective is to check periodically that the shot stream's indentation ability is being maintained after the original set-up curve has been produced.

Single-strip T-testing is a straightforward test with the clearly-defined requirement that the measured arc height for a strip peened for a designated time, T, has to be between stated upper and lower limits. The test may require either one or more strips to be tested for one or more Almen block locations. If the test is to be effective then control has to be exercised over both shot stream flux and shot velocity. In practical terms we have to control both shot feed rate and air pressure/wheel speed.

The measured arc height on a single strip will rarely be precisely the same as that predicted from the full saturation curve test. That is because all measurements have unavoidable variability – which can be expressed as a standard deviation. Every Almen arc height measurement is a 'statistic' and collections of statistics are best treated using reliable, appropriate, statistical techniques. The commonest statistical parameter is the 'average' of a collection of values. A 'normal distribution' of values has two parameters: the average or mean, μ, and the standard deviation, σ, of the values. 'Confidence limits' are defined as the probability that a measurement will lie within those limits. Hence '95% confidence limits' would be plus and minus two standard deviations from the mean. '99·7% confidence limits' are plus and minus three standard deviations from the mean. Confidence limits will only be maintained for actual measurements if there is no change in mean arc height. Again that means that we must control both shot velocity and shot stream flux.

Multi-block T-testing is more complicated than single-block T-testing. Some components require an array of several Almen blocks – in extreme cases more than twenty – for the set-up saturation intensity determination. Intermittent confirmation testing may then require single strips to be tested at the same time at all of the locations. That 'same time' cannot correspond to the saturation point 'time' for all of the test blocks. Each block will have yielded a different saturation 'time'. One reasonable way of handling the situation is to take the mean of the saturation times derived for all of the locations involved and require that the nearest integral 'time' be used - with compensating adjustments to the required arc height limits.

Two-strip T-testing is required by some users. This involves tests being carried out at two different peening times, T and 2T, with a requirement that the arc height at 2T will be less than 10% greater than that at T. The test is more rigorous and more complicated to analyze than single-strip T-test confirmation.

DISCUSSION

Every full Almen saturation curve is a confirmation test of a shot stream's required indentation ability and is therefore an essential part of quality control. The curve yields an internationally-accepted parameter, the so-called "saturation intensity", whose derivation is classically simple – using either manual or computerized curve-fitting procedures. Saturation intensity is a high-curvature point of the saturation curve – it is not a data point. *Continued on page 30*

Continued from page 28

Saturation time can be used as an indication of the shot stream's coverage rate. With computerized curve fitting procedures the derived saturation point is determined objectively and it is possible to quantitatively relate actual curves to those that would be anticipated.

The objective with T-testing is to confirm that the required saturation intensity is being maintained during a production run. It cannot, however, guarantee that this intensity is being maintained. That is because different saturation curves can intersect at the specified saturation point. Consider, for example, the situation illustrated by fig.5. A set-up saturation curve is shown, together with the corresponding saturation point, Ts. A second saturation curve is shown which could easily have arisen during a production run if the shot flow rate had been substantially reduced – hence inducing increased shot velocity (if air-blast is being employed). The second curve has the same Almen arc height at Ts as the set-up curve, but has a different saturation intensity, Tc. Hence, a confirmation T-test would not reveal that the saturation intensity had in fact substantially increased.

Two-strip T-testing is difficult to quantify reliably. It cannot be either as effective or as reliable as a full saturation curve. The use of full saturation curves should, therefore, be the preferred practice, especially for critical applications.

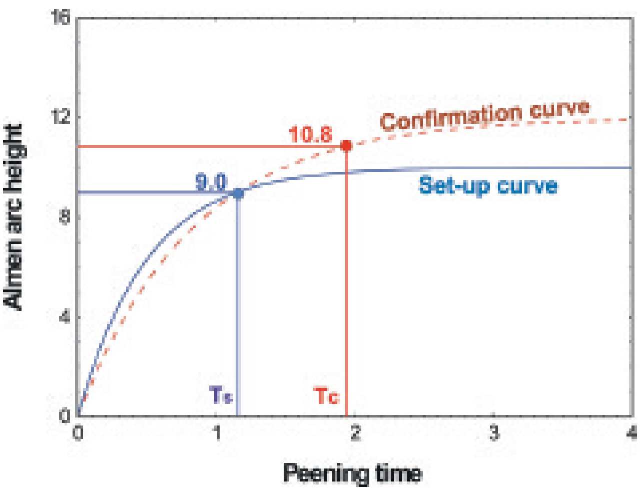


Fig.5 Identical arc heights obtained at Ts with different saturation intensities.

CONCLUSIONS

1. Saturation intensity is a reliable, primary, quality control parameter. It is a high-curvature point of the saturation curve – not a data point.
2. Computerized curve-fitting has substantial advantages relative to manual curve-fitting.
3. Single-strip T-testing for confirmation testing is useful provided that effective control is exercised over both shot flux and shot velocity.
4. Saturation curves can provide a useful indication of coverage if an appropriate allowance is made for the relative indentation resistance of Almen strip and component material.