# ALMEN STRIP VARIABILITY - A STATISTICAL TREATMENT

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## ABSTRACT

Repeatability of Almen strip arc height measurements has been determined for both A and N strips. Repeatability estimates are based on exposing multiple strips under constant peening conditions. The effects of media, fixture orientation and type of machine on arc height variation have also been investigated. This paper discusses the amount of Almen strip variability observed and its implications for defining the saturation point; and, offers a recommendation for peening intensity limits based on process capability.

Key Words: Peening, Shot Peening, Almen Strip, Almen Strip Repeatability

## INTRODUCTION

Peening has gained wide industry acceptance as a means of mechanically treating the surface of metal components to enhance their fatigue lives. The introduction of a compressive stress within the first few thousandths of an inch below the surface serves to retard crack initiation and to slow the growth of a crack once it has formed. The depth of the compressive layer is governed by the size and velocity of the peening media. Although the effect of peening will vary for different alloys, the curvature of a peened hardened and tempered carbon steel test strip (Almen strip) is used as a standard to qualitatively define the depth of compression. The curvature is measured in ten thousandths of an inch on an Almen gauge with a digital indicator. The reading, when combined with the thickness of the test strip, is a measure of peening intensity.

A properly peened Almen test strip and the part it represents require full surface coverage by the spherical peening media which may consist of any one of these diverse materials: conditioned cast steel shot, conditioned cut wire steel shot, glass beads and ceramic beads. Full coverage is achieved when the media produces sufficient overlapping dimples to obliterate the original surface texture. When approaching full coverage, the rate of gain in Almen strip arc height with respect to peening time begins to diminish. As peening continues, further increases in the arc height are usually minimal. The saturation point on the test strip is usually defined as the time which, when doubled, produces no more than a 10% increase in the measured arc height.

Ideally, test strip response to the same peening conditions should be uniform; that is, identical arc height readings should result on successive strips. Unfortunately, this is not precisely the case. The work described in this paper deals with arc height measurements taken on repetitive strips exposed to the same peening conditions. Analysis of the data demonstrates that arc height measurements for a stable peening process can lead to wide variation in saturation time estimates. That is, repeatability measurements taken at the saturation time and double the saturation time may not validate the 10% rule due to random variation in arc height measurements.

## DESCRIPTION

A series of Almen strip arc height readings, compensated for prepeen flatness, were taken for different processing conditions on peening machines located at four production sites. An overview of the peening conditions used in this study appears in Table 1.

The variation of A strips at site A was reported previously by Bailey (1) for a pressure peening machine charged with S110 hard steel shot. Eleven strips were located circumferentially on an 18 inch radius from the center of a rotating table. Peening was accomplished with a single oscillating nozzle positioned with a 6 inch standoff at 45 degrees perpendicular to the strip axis.

Site B utilized a gravity suction machine for steel shot with strips located radially on a rotating table. A group of eight equally spaced nozzles positioned radially at a 45 degree angle moved in a horizontal mode four to six inches above the table. Both A and N strips were measured. Site B also employed a wet glass machine with a similar setup except that eight duckbill nozzles with no oscillation were used to peen N strips.

The steel shot and dry glass machines at Site C, both gravity suction, consisted of fixed nozzles with strips positioned vertically. Strips exposed to overlapping streams of steel shot were rotated on satellite stations as the turntable indexed. Strips peened with dry glass beads made a single pass by fixed nozzles on a slowly rotating table.

Table 1: Summary of Peening Conditions

| Type of strip, A or N | Media type and size | Number of strip orientations | Number of strips at each orientation | Number of measurements beyond saturation time | Arc heights (in. x $10^{-3}$) | Production Site |
|---|---|---|---|---|---|---|
| N | Dry Glass /#5 | 4 | 10 | 6 | 5 to 11 | C |
| A | Steel shot /S110H* | 1 | 33 | 1 | 5 to 7 | A |
| N | Steel shot /S110R** | 1 | 10 | 9 | 10 to 13 | B |
| N | Steel shot /S110R | 3 | 10 | 3 | 6 to 12 | C |
| A | Steel shot /S110R | 3 | 5 | 4 | 3 to 5 | C |
| N | Steel shot /S110R | 1 | 5 | 5 | 5 to 9 | B |
| A | Steel shot /S110R | 1 | 5 | 5 | 3 to 5 | B |
| N | Wet Glass /#5 | 1 | 5 | 7 | 4 to 10 | B |
| N | Wet Glass /#13 | 1 | 75 | 1 | 3 to 5 | D |
| N | Cut Wire/CCW 14*** | 1 | 5<br>10 | 3<br>2 | 8 to 13 | C |
| A | Cut Wire /CCW14 | 1 | 5<br>10 | 3<br>2 | 3 to 5 | C |

* Rockwell C 55-62, ** Rockwell C 45-52, *** Rockwell C 50-55

Site D employed a multiple nozzle arrangement for wet glass similar to that for Site B except the strips were mounted on a rotating fixture located at the center of the turntable. Conventional (round) rather than duckbill nozzles were used, with oscillation. N strips were peened to an arc height of only .003-.005 inch, which is the least amount of strip deflection evaluated.

The broad variety of peening conditions examined in this study has enabled the authors to statistically analyze the magnitude of Almen strip variability for several peening media in typical production environments in order to establish process capability.

## RESULTS AND DISCUSSION

Potential causes of variability in Almen strip arc height readings are numerous; fluctuations in air pressure and shot flow, strip hardness and flatness, strip and fixture cleanliness, and strip orientation to the shot stream to list a few. Unpublished data collected by Champaigne (2) have suggested that the Almen strip source can be a significant contributor to the variation in arc height measurements. If the Almen strip is indeed a factor of major importance, the non-uniform peening response of individual strips, lot to lot, and between manufacturers will have a significant impact on results since the Almen strip is currently the only accepted method for determining peening intensity. The data below quantifies the amount of Almen strip variation for constant conditions. The discussion suggests possible resolutions for this variability condition.

### Observed Almen Strip Variability

The data presented represents the observed variability of corrected arc heights for multiple strips peened under identical conditions. All reported variability estimates occur at times greater than saturation and full coverage. That is, as indicated in Figure 1, variability estimates do not include the potential increased variation one would expect to see near the knee of the saturation curve.

Multiple variability estimates (sample standard deviations) were obtained for both A and N strips from four peening sites (suppliers) and for six types of media. Typically a subgroup of 5 to 10 strips was peened at identical conditions and times. Multiple observations were collected for 3 to 9 peening times beyond

100% coverage. The range of arc heights investigated was .003 to .007 inch for A strips and .003 to .013 inch for N strips. Sample variances and standard deviations were calculated for each subgroup of Almen strips exposed to identical peening conditions using the standard formula for variance as follows:

$$\sigma^2 = \sum_{i=1}^{n} (x_i\text{-xbar})^2/(n-1) \qquad (1)$$

where $\sigma^2$ = variance
$\sigma$ = standard deviation
xbar = the subgroup average
$x_i$ = the ith individual arc height reading
n = the number of observations in a given subgroup

The pooled variance and associated standard deviation is a measure of peening measurement system repeatability. A strips demonstrated about one half the variability of N strips as shown in Table 2 below, significant at $p < .01$. That is, the probability of A strip variability being equal to N strip variability is less than 1 percent. Fisher's "F" test was used to determine if observed variability differences were significant.

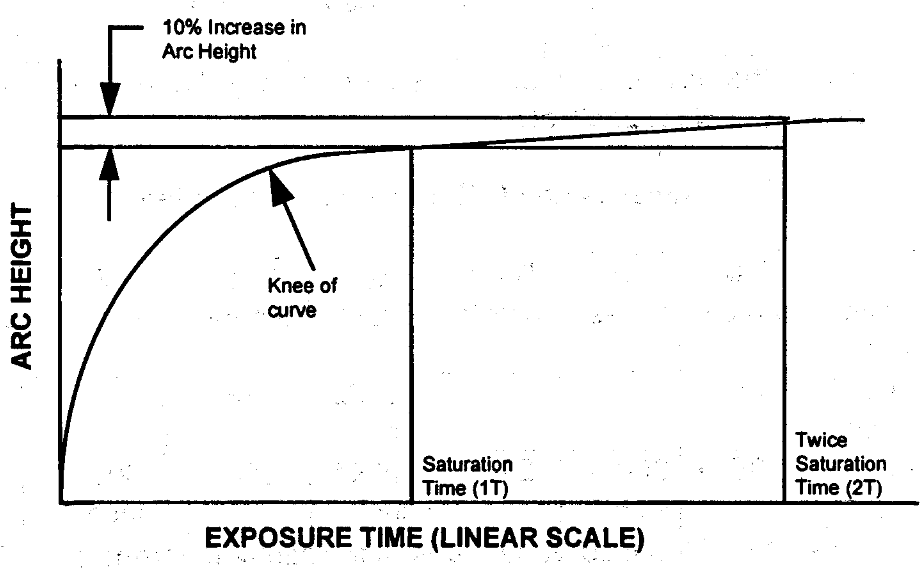


Figure 1: Sketch of Saturation Curve for Almen Strip Peening

Table 2: Observed Variation (Sigma) for Individual Almen Strip Arc Height

| Type of Almen strip | Observed standard deviation, sigma | Number of subgroups of size n | Total sample |
|---|---|---|---|
| A | .00022 inch | 20 groups of size 5, 2 of size 10, 1 of size 33 | 153 |
| N | .00038 inch | 15 groups of size 5, 44 groups of size 10, 1 of size 75 | 590 |

The A and N strip variation versus production site and media are detailed in Table 3 and 4 below.

Table 3: Almen A and N Strip Sigma versus Production Site

| Almen strip type | Site A | Total sample | Site B | Total sample | Site C | Total sample | Site D | Total sample |
|---|---|---|---|---|---|---|---|---|
| A | .00027 inch | 33 | .00028 inch** | 25 | .00017 inch** | 95 | | |
| N | | | .00035 inch | 150 | .00040 inch | 365 | .00029 inch** | 75 |

Note: ** indicates that identified variance is significantly different, p< .05, from average variance, A or N respectively.

Table 4: Almen A and N Strip Sigma versus Media

| Almen strip type | Cut Wire Steel | Total sample | Dry Glass | Total sample | Cast Steel | Total sample | Wet Glass | Total sample |
|---|---|---|---|---|---|---|---|---|
| A | .00020 inch | 35 | | | .00022 inch | 118 | | |
| N | .00051 inch** | 35 | .00034 inch** | 240 | .00041 inch | 205 | .00033 inch** | 110 |

Note: ** indicates that identified variance is significantly different, p< .05, from average variance, A or N respectively.

As shown in Table 3, there can be up to +/- 25% change in standard deviation for A or N strip arc heights by site. The lower variability observed for N strips at site D may be due to a lower average arc height for this application. While A strip standard deviation data did not show a difference relative to media (Table 4), the N strip data experienced 13% lower sigma for wet and dry glass while conditioned cut wire had 30% larger sigma compared with cast steel shot.

Almen strip variation for high quality strip suppliers is consistent, within a +/- 30% band, for the four production sites and six types of media. Although certain sites and media had somewhat larger or smaller variation, the variability of strips is a reality which must be included during setup and monitoring of peening processes. The average variation in A strips was $\sigma$ = .00022 inch which, at an approximate 95% confidence interval (CI), coincides to an individual A strip arc height reading of +/- .00044 inch. Similarly, the average variation in N strips was $\sigma$ = .00038 inch, equivalent to an individual N strip reading of +/- .00076 at an approximate 95% CI.

An unpublished study by Champaigne (2) found the Almen strip source can influence strip variation. He found that two suppliers had an A strip sigma equal to ~.0002 while a third had a sigma ~.0004. The .0002 variation observed for two sources reinforces the variation reported in this paper.

Effect of Almen Strip Variability on Calculated Saturation Point

Saturation is defined as the percent increase in Almen strip arc height for a doubling of peening time. Referring to Figure 1, 10% saturation occurs when the arc height curve has flattened such that the arc height at time 2T minus the arc height at time 1T is 10% of the arc height at time 1T.

A typical N strip peening requirement is an average arc height of .006 to .012 inch and 10% saturation. Consider a peening process which reaches full coverage at time 1T with an associated arc height of .008 inch. The process also meets the 10% saturation requirement at time 2T. That is, the true arc height reading at 1T is exactly .008 inch and at 2T is exactly .0088 inch. Figure 2 sketches the saturation curve and indicates, with normal distributions, the expected measurement system variation for individual N strip arc heights.

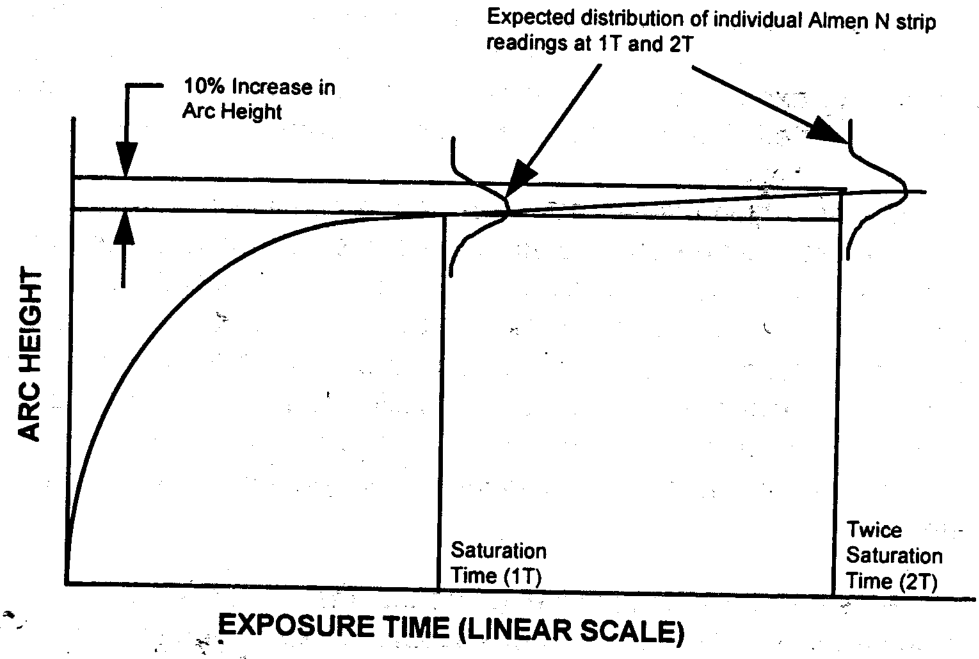


Figure 2: Effect of Almen Strip Variation on Saturation Curve

Almen strip variation can easily lead to calculated saturation values that are misleading. In this example, the "true" N strip arc height at time 1T is .008 inch, but the observed reading for any one strip will vary. One would expect the observed reading to be within +/- 2 sigma of random variation 95% of the time. This is an approximate 95% CI for a normally distributed variation. Since N strips have sigma = .00038 inch (Table 2), the observed arc height for a single N strip will range from .008 -2(.00038) or .0072 inch to .008 +2(.00038) or .0088 inch. Similarly, at time 2T, the observed arc height will equal .0088 inch +/- 2 sigma or a range of .008 to .0096 inch. Due to this expected variability in observed arc height, the calculated saturation could range from a negative 9% (.0088 at 1T to .0080 at 2T) to a positive 33% (.0072 at 1T to .0096 at 2T). This -9% to +33% estimate for calculated saturation is approximately a 99.9% CI, due to combining the probabilities at 1T and 2T.

One approach to reduce the effect of Almen strip random variation is to use multiple strips when defining the saturation curve. An average of 4 strips at each location will have 1/2 the variation of an individual strip, or a 95% CI of +/- .00038 inch versus .00076 inch for N strips. An average of 9 strips has 1/3 the variation or a 95% CI of +/- .00025 inch versus .00076 inch for N strips. The 99.9% CI on saturation estimates for this example will now range from 0% to 21% for an average of 4 strips and from 4% to 17% for an average of 9 strips versus a range of -9% to +33% for a single strip.

The random variation which exists for Almen strip arc heights adds uncertainty to saturation estimates. This uncertainty can lead to overly optimistic or overly conservative estimates for any given percent saturation requirement. Multiple strip observations can reduce the variation in calculated saturation time, but this becomes a key cost factor when part lots are small and numerous setups are needed to meet Just-in-Time production requirements.

The problem has been resolved in one special application involving N strips where a saturation value of 15% has been allowed by the engineering specification. Use of this practice, when appropriate, will substantially reduce the number of N strip readings required to release a peening process for production.

Almen Strip Variation and Setting Limits

Many industries are working to achieve 6 sigma quality levels in manufacturing and support processes. A six sigma process is one in which the process variation, sigma, is low enough so that the process width, xbar +/- 3 sigma will fit within the middle 50% of the tolerance range. Certainly to have a six sigma process, one must have the ability to measure variable outcomes precisely enough so that gage variation, measured as +/- 3 sigma, is less than 50% of the range allowed for the process.

Almen N strip arc heights have +/- 3 sigma variation of +/- 3(.00038) or a total range of about .0023 inch. Almen A strip arc heights have +/- 3 sigma variation of +/- 3(.00022) or a total range of about .0013 inch. Since gage variation, that is strip arc height variation under constant conditions, is only one of the sources of variation in a peening process, a tolerance of more than twice the strip random variation process width is recommended. Setting the random variation +/- 3 sigma process width to 40% of the overall range leads to a suggested tolerance band of .006 inch for N strips and .004 inch for A strips.

## SUMMARY

Almen strip variation is consistent, within a +/- 30% band, for numerous sites and several peening media. The average variation in A strips was $\sigma$ = .00022 inch and the 95% confidence interval for an individual A strip arc height reading was +/- .00044 inch. The average variation in N strips was $\sigma$ = .00038 inch and the 95% confidence interval for an individual N strip reading was +/- .00076 inch.

The random variation which exists for strip arc heights adds uncertainty to saturation estimates. This uncertainty can lead to overly optimistic or overly conservative estimates for any given percent saturation requirement. Multiple strip observations can reduce the variation in estimated saturation. A saturation value greater than 10% is also an option as long as other requirements (e.g. full peening coverage) are met.

Almen N strip arc heights have a process capability +/- 3 sigma variation of +/- 3(.00038) or a total range of about .0023 inch. Almen A strip arc heights have process capability +/- 3 sigma variation of +/- 3(.00022) or a total range of about .0013 inch. Gage variation, that is strip arc height variation under constant conditions, is only one of the sources of variation in the peening process. Air pressure and shot flow tolerances, as well as strips mounted at various angles to the shot stream to simulate part configuration, also add variation. The summation of all of these effects suggests a specified process range for intensity on engineering drawings of .006 inch for N strips and .004 inch for A strips.

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