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IN THIS ISSUE

ALMEN STRIP AS PROCESS CONTROL FOR SHOT PEENING

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Increased attention to process control for quality manufacturing in the 1990's will be necessary. How do we provide a quality program for shot peening? This article will discuss the use, and the abuse, of the Almen strip.

Most manufacturing processes are conducted in a manner that allows some degree of measure of variation in intended results. Properties, such as size, weight, shape, color, etc., can be compared to a standard. Unfortunately, the shot peening process has not allowed a direct (and non-destructive) measure of process results. We peen an item. It appears to have been peened. We test a few pieces and then ship the rest to our customer. "Good luck. Let us know how it worked."

Usually, we aren't that cavalier in our process. In fact, we do a good job to ensure a high degree of process consistency by monitoring whatever parameters seem to be important.

We specify the shot by defining its material, size, roundness, density, cleanliness. We expect a certain degree of coverage by controlling exposure time and shot flow rate. We attain an intensity by aiming (targeting) and velocity control (wheel speed or air pressure).

All of the above process variables can be monitored and charted. The chart can display unusual or out-of-tolerance conditions. And this can be helpful. But none of the above measures the peening quality, at least not directly. Another measure we can introduce to further enhance our confidence is a sample test coupon, commonly known as the Almen strip.

The theory is this: If we can expose the sample test strip to the shot stream in a manner that is nearly identical to the actual process, and if we analyze the results exhibited by the test strip, then we can have a measure of all of the process contributors. We can then focus on the entire process by analyzing or measuring the Almen strip.

John Almen recognized the paramount importance of process consistency, and his contribution to peening quality control is unrivaled. He devised a method of exposing one side of a test strip to the shot stream. Impacts on one side only cause that side to stretch, and therefore curve. The amount of curvature is measured and recorded as arc height using a special gage. The Almen strip test coupon can reveal process variations. If any of the process variables change, then the Almen strip will change. If the shot size is too large, the Almen strip shows a greater curvature. If velocity is too high, the curvature increases. If coverage is substantially too low, then the Almen strip curvature may be low also.

DOMINANT VARIABLES
(increasing variable results in increased curvature)

a. shot size
b. shot velocity
c. shot exposure time up to a limit [1]
d. shot flow rate up to a limit [2]
e. shot impingement angle up to 90°

It would seem, therefore, that monitoring the five dominant variables and controlling them within certain limits should result in low variation [3] Almen strip readings.

So that we don't stray too far from real world practice, suppose the following criteria are required:

1. Peen all over to 10 A
2. Peen all over to 8 - 12 A
3. Peen all over to 8 - 10 A

Common practice [4] indicates that 1 and 2 are identical. Whenever a tolerance is not listed it is assumed to be ±2. Obviously, requirement 3 is stricter. Before going much further, let's establish why we are peening to an intensity. It's because:

- that's how we have always done it.
- that's how our competition does it.
- that's a common value I heard of once.
- we tried it. It works.
- the metallurgist said to do it that way.
- the mil-spec suggested this value for the material.
- through extensive testing, we optimized our product quality and found that this intensity range gives us exactly what we want. Intensities above or below the range do not achieve our goals. [5]

Shot peening places the surface and near sub-surface into compression. The following diagrams,

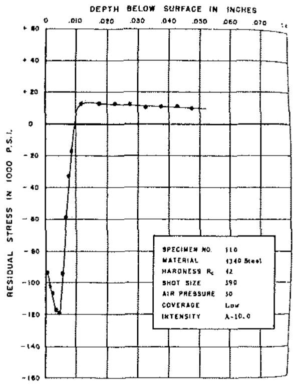

Figure 1

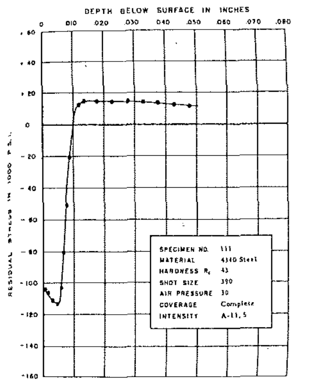

Figure 2

Fig. 1, 2, which only a metallurgist could love, show how different intensities produce different stress profiles. Since the metallurgist knows the shape of the profile he wants, it ought to be easy for the peener to do what P. T. Barnum said: "Give 'em what they want."

I presume the metallurgist knows what stress profile he wants. I assume that he knows what he is doing in specifying a peening intensity.[6] At any rate, an acceptable range of peening intensity is requested and a tolerance is established.

The responsibility now falls to the peener to perform his magic to produce the desired profile. How can he know it is done correctly? How can he know it is done consistently? The problem is, he cannot. The most he can "know", is that he can measure an Almen strip and calculate an "intensity." The machine may vary during production; this may not be detected by Almen strip readings. Although our task sounds impossible, we proceed the best we can. We vow to tighten our tolerances in the five dominant variables and keep the intensity within the acceptable limits.

Since we assume the intensity range is valid, we need to establish:

1) how to measure intensity
2) what factors might influence our measurement

How to measure intensity is described in various documents, namely, MIL-S-13165 and SAE-J-442. Basically, it involves:

1. exposing a new Almen strip to the shot stream in a manner similar to part exposure and measuring its resulting curvature (arc height)
2. continuing exposing additional new strips, each for longer time durations
3. plotting the results showing curvature versus exposure time
4. "reading" intensity by determining where the knee of the curve is located. The knee is defined as that first point on the curve whose value does not increase by 10% when the time of exposure is doubled. [7]

Now that we know what is expected and how to measure it, let's investigate some possible problems. We know that shot size will influence our intensity, so we specify shot size. We also need to monitor and control shot size; otherwise, our intensity will change. What tolerance shall we place on shot size? Sounds like a ridiculous question, doesn't it? Everyone knows that someone else has already established tolerances for shot size. I only have to tell purchasing:

- o cast steel shot
- o S390
- o standard hardness
- o Mil-S-13165

But, let's evaluate this. What happens if I were to substitute S-330 or S-460 shot? Obviously, we would have first a lower, then a higher, intensity. Let's try it and graph the results, then superimpose the graphs of all three shot sizes onto one graph. Draw a vertical line on the S-390 curve at its knee, then read the variation of intensity that results due to shot size variance. You just did a sensitivity analysis. If you thought you had S-390 shot that would give a certain intensity—but you actually used S-330 — you know now, with some degree of certainty, what will happen. This experiment now leads us to wonder about the tolerances "chosen by others" that we use.

We commonly think that S-390 shot has a nominal diameter of 0.0390 inches. Not only is that not true, what do you suppose the size distribution looks like? Take 1,000 pieces of S-390 shot and measure the diameter of each piece with a micrometer. Establish sorting bins in increments of 0.010 inch. All pieces between 0.0385 and 0.0395 fall into the center bin, etc.

Now count how many pieces are in each bin and plot the quantity versus size (called a histogram). How many particles were in the 0.0385-0.0395 bin? How many particles were close to S-330 shot? How many particles were close to S-460 shot? Don't overlook the concept that S-390 shot is actually a collection of particles that range in size. Some "large" S-390 shot can be larger than "small" S-460 shot and still qualify per our specification for shot quality.

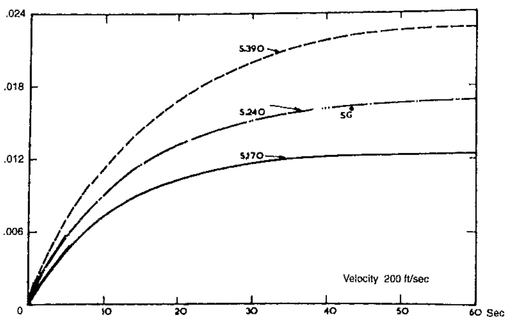

Figure 3

So what? We know the distribution of shot size and can now infer the distribution of intensity; because we know the influence, sensitivity, of shot size versus intensity.

Distribution of intensity? That's right. Mother Nature is in charge. She provided a distribution of particle size, and she is going to provide a distribution of peening intensity. It's called probability distribution and, like it or not, these are the rules.

Don't like what this implies? Then:

- o Use only shot from the bin with size 0.0385-0.0395
- o Change your vocation
- o Learn how to play by the rules

If, by chance (no pun intended), you choose the last option, read on.

You're probably thinking:

- o Let's use cut wire shot for a narrow range of size.
- o Let's be sure the screens are working to separate the shot (by size) properly.
- o Let's monitor everything we can measure and put a tight tolerance on it.

Hold on! Don't panic. You may or may not need cut wire shot. It's not difficult to determine - I already gave you a short course on sensitivity analysis. Naturally, your screens are periodically checked. Right? The last option presents a challenge, but no more difficult than analyzing shot size. You can explore shot flow rate sensitivity using the above techniques. Shot velocity is a little bit more difficult. For wheel systems, the wheel speed is generally related "close enough" to shot velocity to determine its sensitivity. For air peening systems, you can vary the air pressure and draw graphs for sensitivity. You can now specify wheel speed and its tolerance to keep you within the metallurgist's intensity, or air pressure, and its tolerances.

Many people might choose a 5% or 1% tolerance and assume that the intensity variations are stable and minimized. I don't know if that is true or not. But you now have the tools needed to determine what tolerance is appropriate. If your peening pressure is commonly 60 psi—and if your sensitivity is +10 psi/point (i.e., increase air pressure to 70 psi to change the intensity by 1 point or 0.001)—you know that you must specify 60 psi ±20 psi, if you have any hope of maintaining 10-14 A intensity with a ±2 tolerance (and that is with no other variations).

Now, don't jump ahead of me. I know you just thought, "I'll specify 60 psi ±5% and nail down that variable before I go tackle another." Just be patient. Let's sit back and look at the other variables. If you arbitrarily choose a tolerance (due to expediency), you have defined a boundary condition which requires effort to maintain. This "cost" may or may not be worth the benefit. If you insist on 60 psi ±5%, the operator, or some automatic equipment, must now monitor and control to that level of performance.

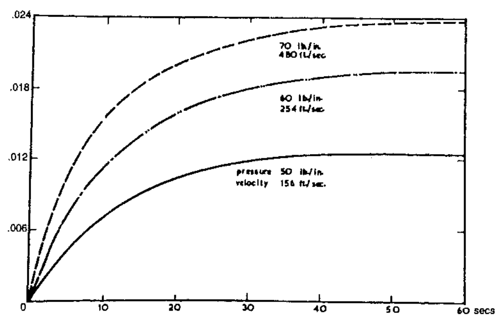

Figure 4

Then, someone is going to ask,

- o Where do you measure the pressure, at the manifold? At the MagnaValve? At the nozzle?
- o Do you use a gage or a transducer? When was it calibrated? When does it have to be re-calibrated? Who is responsible?

- o Do you have a plan to measure hose wear?

Before we establish a tolerance for air pressure, let's repeat the list of important variables:

a) shot size
b) shot velocity (wheel speed or air pressure)
c) shot exposure time
d) shot flow rate
e) shot impingement angle

(I am assuming that shot cleanliness is not an issue, since dust collectors and separator screens are OK.)

The list of five dominant variables isn't really very awesome. You can determine the sensitivity of each item and then assign allowable tolerances to each. How do you assign tolerances? Very carefully. In fact, I'm not sure how to do it. I know how *not* to do it.

- o Do not pick values that, when added together, total the limit of 10-14A. The reason is that this represents worse case conditions, not probable or likely conditions. You have to realize, since we are dealing with probability distribution functions, that the probability of two variables both behaving at boundary conditions at the same time is very remote. A system of five variables is even more unlikely to experience five simultaneous boundary conditions.

In other words, if you have a total tolerance range of ±2, and you have five variables to contend with, don't equally divide the responsibility at ±0.4. In some cases this may not be possible. Some process variables may not be capable of maintaining ±0.4 pt control. As stated above, you are not likely to have all five at boundary conditions simultaneously.

- o Don't pick 5% or 2% or 1% tolerance just because that is the performance level a vendor can provide - unless that tolerance is within your total range. For example, wheel speed tolerance of 1% is easily provided by many vendors. You discover, by sensitivity analysis, that wheel speed can vary by 35% before intensity changes by ±2 points. I think we can agree that wheel speed variations of 1% won't corrupt our process.

On the other hand, suppose the best performance the vendor had available was 20% speed variation; and your sensitivity analysis indicates that 20% speed variation causes ±4 point change in intensity.
Now we have a problem.

So how do you pick the tolerances? I already told you, I don't know. But I have some suggestions. Let's list what we know and go to other topics. By this I mean, let's rank the sensitivities of the five dominant variables, see which is most sensitive and least sensitive. Then, let's pay attention to the most sensitive, get it under control, and proceed to the next most sensitive.

If I walked into this conversation absolutely cold, knowing nothing about shot peening (not too bad of a description according to some), I would tend to do the following:

> As a first guess, I would try to get each of the five variables to be constrained to 1/2 of the allowable range, which in our case would be ±1 for the total range of ±2.
>
> If I know what the air pressure sensitivity is, I would then pick a tolerance that would allow ±1 point (for half of the allowable ±2point range). Then sensitivity for flow rate, angle, etc., can be determined in a similar manner.
>
> If the values chosen for individual tolerances are practical (commercially available at a reasonable cost without undue burden for maintenance and calibration), then we are done. If the value required is more stringent, then you'll have to decide what cost you are willing to pay to receive the benefit.
>
> You tend to limit your costs by using this approach. It doesn't make much sense to insist that shot flow rate be accurate to 5% if air pressure is the high sensitivity variance. Making flow rate accurate to 2% won't give a more consistent peening intensity, while air pressure is still allowed to corrupt the process by ±3 (for example).
>
> The important point here is, to address the highest priority variance and try to get that tolerance to one-half the allowed range; then, address the next priority, and so on, until all five are at 1/2 tolerance, or as low as you can practically get it.

Enough of theory. Let's get to practice. Suppose we have set up a machine and run five Almen strips and plotted a graph, and read the intensity, and we get a value of 13A. Hooray! We are within the target range of 10-14A. Now, let's keep it there.

How do we do that? Read on.

We decide to check intensity once each day. So, each day we consume five Almen strips, plot a graph, and read the value. Being curious, we further decide to make an additional graph that represents the intensity on a daily basis. It won't take long before someone suggests that we treat this like an SPC chart; we can reveal C_p and C_{pk}, etc., etc., etc. (I love it!)

Now, to be cautious. Someone is going to say, "That's a lot of Almen strips; let's just run one strip per day and chart that value." What is wrong with that? Plenty!

First, to make a chart of *intensity,* you must be able to measure and record *intensity.* The word *intensity* is interchangeable with the words "knee" and "saturation". A single data point does not "graph" a knee. Repeat after me 100 times:

A single data point does not graph a knee (saturation, intensity)...
A single data point does not graph a knee (saturation, intensity)...

The mil-spec on shot peening, MIL-S-13165, clearly states, **to determine intensity, you <u>will</u> construct a graph and read the value of the <u>knee</u>.** You cannot do this with a single data point.

Still want to argue? Ok, do one strip at the time found to be needed to reach saturation (from day one); then, run a second strip at twice that time. If the second strip is within 10% of the first strip, then we are at saturation and we know the intensity.

Repeat after me 100 times:

Two data points do not graph a knee, saturation, intensity...
Two data points do not graph a knee, saturation, intensity...

Connecting two data points by a line does not reflect Mother Nature's view of the process. See Appendix A.

Why am I so harsh on this? Several reasons. Go back to last month where you have 30 days of graphs using five Almen strips. Plot all of the data onto one graph and look at the data scatter. It's easy to draw a single line using a French curve and using the mid-point of the data presented, and this represents the <u>average</u> (remember probability distribution). How many lines can you draw if you connect specific data points ? If you couldn't remember which data point represented which day - but still drew a line - what range of values of intensity do you think are available ? Then, look at the data scatter near the knee.

Suppose you performed all of the sensitivity analysis outlined earlier, and you have achieved control within ± 1 point. What else can go wrong?

The mil-spec allows for Almen strip flatness (pre-bow) variation of ±0.001 inch. Experiments show that Almen strip pre-bow will directly affect curvature, namely:

(+) 0.001 Pre-bow	= 14A
"Perfectly flat"	= 13A
(-) 0.001 Pre-bow	= 12A

But wait. There's more...

The mil-spec allows a hardness variation of from R_c 44-50 for the Almen strip. Tests indicate that this six-point spread in hardness will influence the arc height by 0.0006 points. That's in addition to the flatness problem. But wait, there's more...

Whoever said the Almen gage was accurate? When was it calibrated? Could it be off by ± 1 point? Remember the article on Almen gage accuracy and the influence of ball flatness? Did you ever watch an operator slide the Almen strip back and forth on the gage to get the highest reading? (SAE wants to use an end stop to define the position used for strip reading.) Variations of ± 1 point are not uncommon.

All right, now that I have you irritated, confused, etc., let's converge on some conclusions.

1. Monitor and control of the five dominant variables are necessary, but not sufficient, to achieve long term control.
2. Almen strip reaction to peening combines the influence of the five dominant variables and gives a composite indication of peening intensity.
3. Intensity is influenced by each of the five variables to a certain degree, as indicated by sensitivity analysis.
4. The metallurgist wants a particular stress profile.
5. Variations in Almen strips may corrupt arc height and, hence, intensity readings.
6. Recognition of probability distributions helps to show, on the average, what is happening.
7. Use of one or two strips does not evoke confidence in a conclusion.
8. Intensity, knee, and saturation are interchangeable terms.
9. Intensity readings require graph charting and reading.
10. You cannot measure (directly and nondestructively) peening quality. You must therefore monitor and control the five dominant variables and monitor the <u>intensity</u>. That's <u>intensity</u>, not single-point data or two-point data, but <u>intensity</u>, as in five data points, a graph, a best-fit curve, an interpretation.

CONCLUSION

Measuring the five dominant process variables is not sufficient to assure peening consistency. Proper use of the Almen strip will enhance your peening consistency. Sensitivity analysis can be used to relate peening intensity to product fatigue life. Sensitivity analysis can also be used to relate each of the five dominant process variables to peening intensity.

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[1] Exposure of Almen strip to extremely long periods, usually 5-10 times the time needed to exhibit saturation, can result in strip curvature reduction.

[2] High increases in shot flow rates in a wheel peening machine may result in congestion at the surface, and you may actually decrease the "effective" coverage. Or, in air peening systems, a higher shot flow rate can drastically reduce the shot velocity and result in a reduced curvature of the Almen strip. Therefore, the assignment of positive relationship is understood to be within boundary conditions stated above.

[3] ...whatever that means. Generally ± 0.002 is deemed an acceptable control limit; but this is subject to much debate.

[4] See SAE J442

[5] This is also called sensitivity analysis. See Appendix B.

[6] It's possible that a metallurgist might ask a peener to experiment with various peening recipes until he achieved a desired profile. But, don't hold your breath.

[7] Knee, saturation, and intensity are used interchangeably. See Appendix A.

◆ ◆ ◆

APPENDIX A - INTENSITY READING

Using the proper technique to read intensity is important to the success of a peening quality program. The following guidelines will provide a consistent procedure:

1. Use a standardized form to record the arc height data. Be sure it includes enough information to clearly identify the process being measured. (You may have to refer to this data a year later. Be sure you have all the information necessary to describe your conditions.) Include such items as:

   a. date
   b. machine identification
   c. operator's name or initials
   d. job number or part description

2. Be consistent with notation. Choose one of the methods below:

1) .003A	1) 3A
2) .006A	2) 6A
3) .008A	3) 8A
4) .009A	4) 9A
5) .010A	5) 10A

3. Represent each data point on the graph using a small symbol, such as a dot or filled circle.
4. Draw a best-fit curve through the dots. DO NOT PLAY "CONNECT-THE-DOTS". The graph should represent, as close as possible, a smooth curve. The fact that a dot may not fall on the curve illustrates an inaccuracy of our measuring techniques. I'll guarantee that Mother Nature uses a curved line, not a segmented "connect-the-dots".
5. Try to ignore, or better yet erase, the dots so that they do not become a distraction to the next step.
6. Intensity is defined as, "That first point of the curve whose value does not increase by 10% when the exposure time is doubled" Slowly move up the curve, applying the above test. It is <u>not likely</u> that intensity may be exhibited at an arbitrary point you selected as a data point.

   Furthermore, the choice of data points should have no influence on the construction of the best-fit-line or reading of intensity. In other words, if you used one-, two-, three-, four-, five-minute intervals, then .5, 1.5, 2.5, 3.5, 4.5 and 5.5 would be equally valid, since we ignore the data point and focus our attention on the best-fit curve.

7. Draw a horizontal line from the knee to the vertical (y-axis). The intercept is labeled "intensity".
8. Anytime you use the word "intensity", you can substitute the word "knee" or "saturation". These terms apply to a graph. The graph is a line, drawn with the aide of a French curve, that best-fits the data points. The line may or may not intersect all of the data points. The time to reach saturation (knee, intensity) may or may not (most likely not) be coincident with a data point. However, this time to achieve saturation (knee, intensity) is not to be used for any process control (unless your business is comprised of selling peened Almen strips).

Once you have adopted this technique, you may notice the affect that data-scatter can have on intensity readings. The best-fit curve is appropriate, because it tends to average the results; and it is indeed important to treat our data this way, since we are dealing with probability distribution functions . A few comparisons using two data points for intensity versus best-fit curve will illustrate the validity of the best-fit curve approach.

Examine some of the intensity graphs you have already constructed. Use the preferred technique of intensity reading by focusing on the best-fit-curve. Next, declare the data point closest to the knee as intensity and compare your results.

What would have happened if your time choice had been shorter or longer? Wouldn't it change your reading of intensity? This is why the best-fit curve approach is preferred. It reduces operator-induced bias and accommodates an averaging technique.

Caution: BE SURE TO FORGET the time required to reach saturation for the Almen strip. It is not relevant to your part peening process, or to future intensity readings.

Do not declare a relationship between Almen strip intensity (saturation) time and your processing time. Due to material differences, namely hardness, the time required for complete part peening (100% surface denting) is NOT LIKELY TO EQUAL ALMEN STRIP SATURATION TIME.

Furthermore, even if by coincidence the part exposure time for 100% coverage should happen to equal Almen strip saturation time, the variation in shot flow rate can affect coverage. Don't assume that a fixed exposure time guarantees coverage. A lower flow rate, temporary or permanent, can lead to incomplete coverage. Yet the peening intensity may remain constant. Treat intensity determination and part coverage as completely separate topics.

APPENDIX B

For various intensities, determine product quality and load range (cycles-to-failure, etc.). By plotting the data you can determine the broad or narrow range of acceptable intensities. If the desired cycles-to-failure is 10,000 and intensities of 4-17A provide this performance, then specifying 10-12A intensity is an unnecessary burden. On the other hand, if the performance can only be achieved with intensities of 10-12A, then the requirement is reasonable.

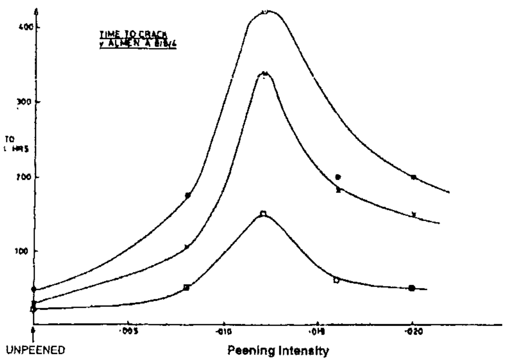

Figure 1

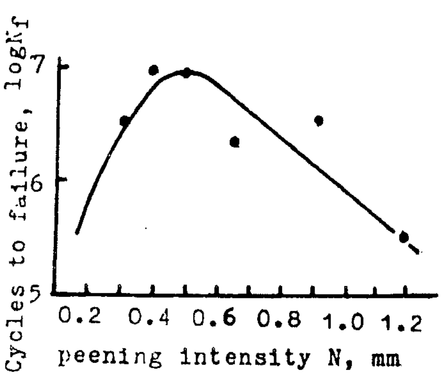

Figure 2

Figure 1 shows time-to-crack (hours) for various peening intensities. Figure 2 shows cycles-to-failure for various peening intensities.