ALMEN STRIP SATURATION CURVE NEEDS REVIEW

VERY DIFFERENT VALUES can be obtained when measurements or experiments are repeated. Sometimes the single values are very close to each other, other times they are far apart. Let's have a look at two batches of numbers. They could refer, for example, to experimental measurements of the same process at different times under different settings.

	Replicates										
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Average
Exp1	9.5	9.9	9.7	10.5	10.1	10.4	9.6	10.0	10.1	10.2	**10.0**
Exp2	7.0	8.0	12.0	9.0	11.0	14.0	8.0	12.0	10.0	9.0	**10.0**

Each experiment has 10 single measurements made at different times that we will call replicates. If we observe the averages of exp1 and exp2 we can notice that they are exactly the same value, but is easy to understand that those two experiments are far from comparable. Exp1 ranges from 9.5 to 10.5 and exp2 ranges from 7 to 14 but they have the same mean value. When we compare different batches of numbers we have to take either the average or the dispersion of the values around the average. The dispersion can be evaluated with a parameter known as "standard deviation." Standard deviation can be estimated as the root mean square of the difference of each single replicate from the mean value divided by the degrees of freedom as represented by the following formula.

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}$$

Where S is the estimate of the standard deviation, n is the number of replicates, X_i is the i_{th} replicate and $\overline{X}$ is the average of the n replicates.

From a statistical point of view, the lower the standard deviation of an experiment, the higher the probability of each single event or replicate to be close to the experiment mean value. From a practical point of view, the lower the standard deviation of the replicates the higher the robustness of the experiment and the higher the "reliability" of each single measurement.

When we compare different batches of numbers with different mean values to judge the robustness or reliability of each single batch, we should use relative standard deviation in place of standard deviation. Relative standard deviation is defined as the standard deviation divided by the mean value of the batch. Relative standard deviation is expressed in percentage. By that way we can say, for example, that a process with a mean value of 20, a standard deviation of 0.8 and a consequent relative standard deviation of 4% is more robust or reliable of a process with a mean value of 10 with a lower standard deviation of 0.6 but a higher relative standard deviation of 6%.

Once we clearly have in mind the meanings of standard deviation and relative standard deviation and how to use them, we can look at the saturation curve.

In his Fall 2012 Shot Peener article, Dr. David Kirk writes, "The most accurate method of estimating peening intensity is to produce and analyze a saturation curve constructed from the arc heights of four or preferably more peened Almen strips." All the recent specifications regarding this issue, included SAE J443, are in agreement requiring a minimum four Almen strips for the saturation curve. Unfortunately, none of the specs seems to suggest a way to distribute the strips within the curve. For what we know so far, once we have T and 2T within the range covered by the four strips it is enough.

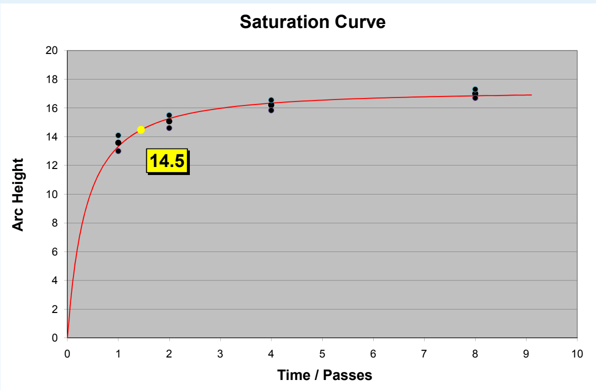
After twenty years daily work, it is my personal opinion that the Almen saturation curve, in addition to what is expressed in SAE J443, should be made at least with one Almen strip before intensity point (the knee) and at least three Almen strips after intensity point. The reasons why are the following.

As shown in our experimental campaign on page 18 called "DoE + Production," the strips after the intensity point show lower relative standard deviation, thereby giving greater statistical meaning than the ones before the intensity point. For that reason, it's convenient to have the greater number of strips after the intensity point. In addition, it is also my personal opinion that we should use the saturation curve not only for determining the intensity value but, just as important, to assess our shot peening production process.

A good saturation curve should flatten after the intensity point but if we don't have enough points to discover and confirm it, we will have no idea if it will flatten. Recording several saturation curves can give us our standard deviation of the strips, of the entire curve and, in the end, of the process. When something falls out of our standard ranges, we have an alarm bell. Once more, from a fatigue point of view, keeping our peening process under strict control is of the utmost importance. These are the reasons why I trust that keeping T and 4T within the range covered by the strips is a more accurate way than only T and 2T. I hope this approach can help to have more robust saturation curves and processes and that it could be a suggestion for a refinement of current specs.

Experimental Campaign "DoE + Production"

A design of experiment was run to investigate the variability of Almen strips. Several machine configuration were examined to simulate different plants and different setups. Design parameters were shot dimension, shot flow rate, hose diameter, and intensity. Sixteen saturation curves were run, each of them with 4 exposure times and each exposure time replicated 3 times. Twelve strips were run for each curve as depicted in the following figure.



A total of 192 Almen strips were used for the experiment. For each exposure time, the mean value, the standard deviation and the relative standard deviation as a percentage of the mean value have been calculated. The mean values and the relative standard deviations of the corresponding time units have been pooled in a "central saturation curve" (figure above) leading to the conclusion that the higher the exposure time the lower the relative standard deviation as shown in the following table.

Pooled Time Units	Pooled Mean	Pooled St.Dev.%
1	13.6	**1.29%**
2	15.1	**1.19%**
4	16.2	**1.03%**
8	17.1	**0.93%**

Shot S110 - S230
Shot flow rate: low - high
Hose diam. 13 - 25
Nozzle 8 mm
Distance 150 mm
Exposure times 7,5/60 to 40/320
Intensity: 8,4 - 21,2 Almen A

192 almen strips used

As a confirmation of the results shown by the experimental plan, two productions were analyzed. Twenty on-going verification curves, considered as 20 replicates, were examined for each single production. Each curve has been constructed by 4 Almen strips, as usual, for a total of 80 Almen strips for each production. In total, 160 Almen strips were analyzed.

Mean values and results are reported in the two following tables. In both production runs, it is possible to see a confirmation of the trend. In particular in those two production runs we have a global lower relative standard deviation in comparison to what obtained in the experimental plan. This can be explained by the fact that in the experimental plan very different machine setups were pooled and analyzed while similar single setups were used in these two production runs.

Production 1			
Time	Replicates MEAN	ST.DEV.	**ST.DEV. [%]**
4	14.6	0.17	**1.14%**
8	16.4	0.15	**0.89%**
16	17.8	0.15	**0.82%**
32	19.2	0.13	**0.67%**

Production 2			
Time	Replicates MEAN	ST.DEV.	**ST.DEV. [%]**
8	14.6	0.17	**1.14%**
16	16.4	0.14	**0.86%**
32	17.6	0.14	**0.79%**
64	18.6	0.13	**0.70%**

Michele Bandini is the General Manager of Peen Service in Bologna, Italy. He is also in charge of the shot peening technology transfer for Ipar Blast, an associate company of Peen Service in Spain. He is a specialist in residual stress measurements with the x-ray diffraction technique and offers his knowledge and experience to the design department of Peen Service's customers.

Mr. Bandini has been involved in numerous studies in shot blasting and shot peening surface treatments. He has co-authored several thesis and technical papers on the shot peening process, its benefits and applications.

In additon, he teaches at the Mechanical Engineering University of Bologna, Trento and Milan.

Mr. Bandini's latest achievement is the 2009 Shot Peener of the year award from *The Shot Peener* magazine.