SHOT PEEN IMPACT ON LIFE, PART 1:
DESIGNED EXPERIMENT USING RENÉ 88DT

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ABSTRACT

Shot peening, long recognized for its potential to increase life capability, can also cause the reverse effect. The results from a designed experiment (DOE) were analyzed to identify shot peen factors (shot size, peening intensity, incidence angle and %coverage) correlating with a decrease in life capability. This paper presents the original data and analysis from the designed experiment. The following two papers present the results from follow-on efforts, including single particle impact tests using production shot to identify material response under a variety of conditions, as well as microstructural evaluation & residual stress measurements for each of the peening conditions investigated. This led to the development of a predictive model which can be used to characterize a lower-bound low cycle fatigue life for the Nickel-base superalloy, René 88DT.

KEYWORDS

Shot peening, fatigue life capability, fatigue damage, designed experiment, Weibull analysis, shot type, intensity, saturation, %coverage, incidence angle, velocity, René 88DT, conditioned cut-wire shot.

INTRODUCTION

The beneficial effects of shot peening have long been recognized. One of the major reasons for shot peening is to induce a beneficial compressive stress layer that acts to retard the development and propagation of cracks from surface features [1, 2]. If crack formation and propagation from surface features can be suppressed, longer component operating lives can often be attained. Dörr and Wagner [3] demonstrated that shot peening was effective in retarding crack propagation of existing cracks, even when peening was applied after the development of cracks. Luetjering and Wagner [4], and others have recognized, however, that shot peening can also cause the equivalent of fatigue damage. This effect has received considerably less attention.

Several years ago, a shot peen DOE was conducted by Bailey [5] to evaluate the effect of shot peening on low cycle fatigue (LCF) life of René 88DT. Life capability at some of the peening conditions evaluated was found to be an order of magnitude lower than that of unpeened specimens tested at the same conditions, supporting the idea that shot peening can "damage" a surface. Life capability at other peening conditions was found to be comparable or slightly superior to unpeened specimens, but with significantly tighter scatter, resulting in higher minimum life capability.

The significance of this study is that it clearly demonstrated shot peening's potential to *reduce* life capability. Various attempts at modeling or predicting the life behavior were not entirely successful. "Damage maps" were developed to "plot" regions of low life behavior, which were then used to establish safe process windows. This paper documents the analysis that was conducted using data from the Bailey DOE.

EXPERIMENT DESIGN

A total of four factors were evaluated at two levels each as shown in Table 1, for a total of 16 different peening conditions. Each condition was tested twice, for a total of 32 tests. Standard smooth round bar specimens, 0.4 inches in diameter were used. The tests were run in strain control at 1000°F, at a strain level chosen to yield an average life of 100,000 cycles for low-stress ground specimens.

Table 1 – Summary of Factors Evaluated by Shot Peen Design of Experiment

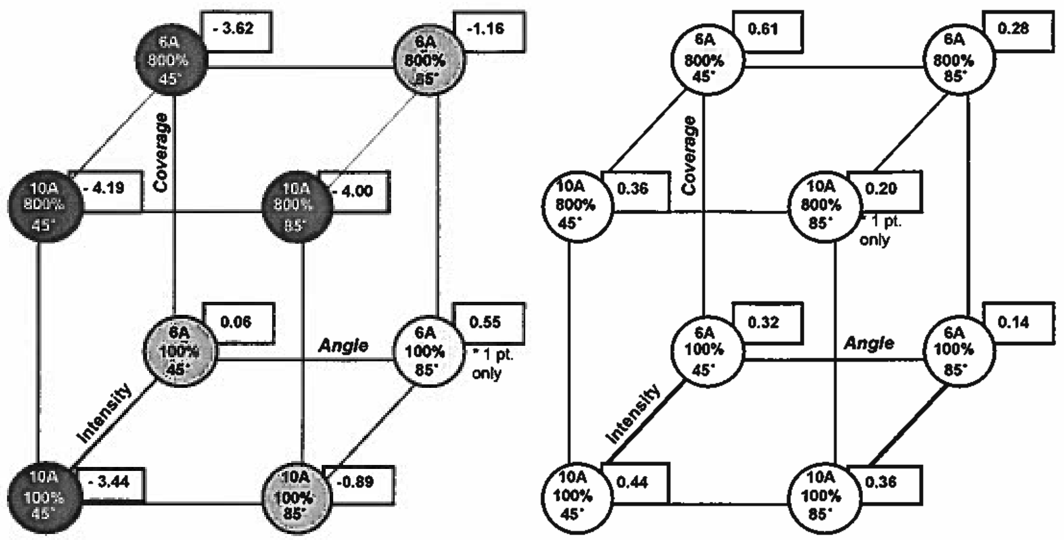
	Factor	Low Level	High Level
1	Shot	CCW14	CCW31
2	Intensity	6A	10A
3	Incidence Angle	45°	85°
4	% Coverage	100%	800%

RESULTS

Figure 1 shows cube plots of the ccw14 and ccw31 peening conditions. Table 2 gives the results in standard order, along with initiation site, life in cycles, and normalized life parameter, "stdev," which is defined as:

$$stdev = \frac{\left[\log\left(N_{obs}\right) - \log\left(N_{avg}\right)\right]}{\left[\log\left(N_{avg}\right) - \log\left(N_{-3\sigma}\right)\right]/3} \qquad (1)$$

Here, N_{obs} represents the test observed life at failure. N_{avg} represents the average life for the stress and temperature condition for a large quantity of low stress grind and polish (LSG+P) data, and $N_{-3\sigma}$ represents the minimum life for that data. As a result, |stdev| > 3 indicates test results which are very uncharacteristic of the average population of LSG+P test results. Approximately 68% of data points should be within |stdev|<1, while 95% should be within |stdev|<2, and 99.7% should fall within |stdev|<3.



a) CCW14 SHOT PEEN DOE

Best condition: low intensity, low coverage, high angle.
Lowest life condition: **high** intensity, **high** coverage, **low** angle.
Statistically significant difference. Color coding: white=good life capability, gray=transition cases, black=low life capability.

b) CCW31 SHOT PEEN DOE

Robust process. No statistically significant differences between effects. All ccw31 data were analyzed as one population for Weibull analysis (Figure 3).

Figure 1 – Cube Plots of Shot Peen DOE

Table 2 – Results of Shot Peen Design of Experiment (DOE conditions are #1-16)

						First Replicate			*Second Replicate*		
DOE cond.	Shot	Peen Int.	Angle	Coverage	*Average stdev*	Init. Site	Life, Nf	***stdev***	Init. Site	Life, Nf	***stdev***
1	ccw14	6A	45	100%	0.06	I	126,779	0.03	I	156,558	0.10
2	ccw14	6A	45	800%	**-3.62**	**S**	**23,598**	**-3.83**	**S**	**29,523**	**-3.42**
3	ccw14	6A	85	100%	0.55	I	163,647	0.55	invalid		
4	ccw14	6A	85	800%	**-1.16**	I	134,393	0.16	**S**	**39,504**	**-2.47**
5	ccw14	10A	45	100%	**-3.44**	**S**	**28,909**	**-3.47**	**S**	**27,203**	**-3.41**
6	ccw14	10A	45	800%	**-4.19**	**S**	**20,253**	**-4.23**	**S**	**21,467**	**-4.15**
7	ccw14	10A	85	100%	**-0.89**	I	138,633	0.29	**S**	**49,529**	**-2.07**
8	ccw14	10A	85	800%	**-4.00**	**S**	**21,621**	**-4.17**	**S**	**22,311**	**-3.83**
9	ccw31	6A	45	100%	0.32	I	137,555	0.29	I	141,969	0.36
10	ccw31	6A	45	800%	0.61	I	141,026	0.21	I	132,206	1.02
11	ccw31	6A	85	100%	0.14	I	143,627	-0.05	I	139,635	0.32
12	ccw31	6A	85	800%	0.28	I	126,348	0.20	I	145,630	0.36
13	ccw31	10A	45	100%	0.44	I	142,725	0.43	I	151,554	0.44
14	ccw31	10A	45	800%	0.36	I	141,723	0.24	I	150,913	0.49
15	ccw31	10A	85	100%	0.36	I	161,649	0.35	I	143,340	0.37
16	ccw31	10A	85	800%	0.20	I	143,004	0.20	invalid		
17	ccw14	12N	45	400%	1.39	I	214,209	1.39	I	243,843	1.63
18	ccw14	12N	45	800%	1.28	I	193,937	1.28	I	188,658	1.23
19	unpeened				-0.59	S	69,436	-0.59	S	48,048	-1.30

In Table 2, shot peen intensity is given in mils of deflection (1 mil=.001 inches), on Almen "A" strip or "N" strip as indicated (thus 6A = .006 inches deflection on an Almen "A" strip). Initiation site: "**I**" = internal initiation; "**S**" = surface initiation; "Invalid" = invalid tests obtained. Tests conducted at 1000°F, R-ratio=0. Actual stresses varied by as much as 6% from target value. For the target stress level, N_{avg} = 96,800 cycles and $N_{-3\sigma}$ = 17,700 cycles. However, "stdev" calculations use values of Navg and $N_{-3\sigma}$ for the actual stress level.

Note that surface crack initiations are highlighted in Table 2 with bold type. In all cases, internal initiation sites provide an indication of a "good" life result, one that is well characterized by average LCF specimen data, having a |stdev| < 2 or 3. However, these lives were not significantly above average. Of the ten peened conditions with a surface crack initiation, eight had lives with stdev < -3. Of the two conditions with -3 < stdev < -2, the other replicate had internal initiations with a "good" life result, perhaps indicating a borderline condition.

In addition to the 16 conditions evaluated by the Shot Peen DOE, results from two light peening conditions (ccw14, 45°, 400% and 800% coverage) are included in Table 2 as conditions 17-18, along with unpeened specimen results (to serve as a benchmark) as condition 19. The light peening conditions are also included in the Weibull analysis of the following section, and in velocity comparisons provided later. Both unpeened specimens had lives slightly below the average values expected.

Analysis of Variation (ANOVA).

The DOE data provide evidence of significant interactions between peening parameters. A total of nine effects, including all four main effects, 3/6 two-way interactions, 1/4 three-way interactions and the single four-way interaction were found to be significant at the 95% confidence level. These factors are listed in Table 3, along with the corresponding probability. Probability values below 0.05 indicate factors having a significant effect on life capability. See Box, Hunter & Hunter [6] for techniques of ANOVA analysis.

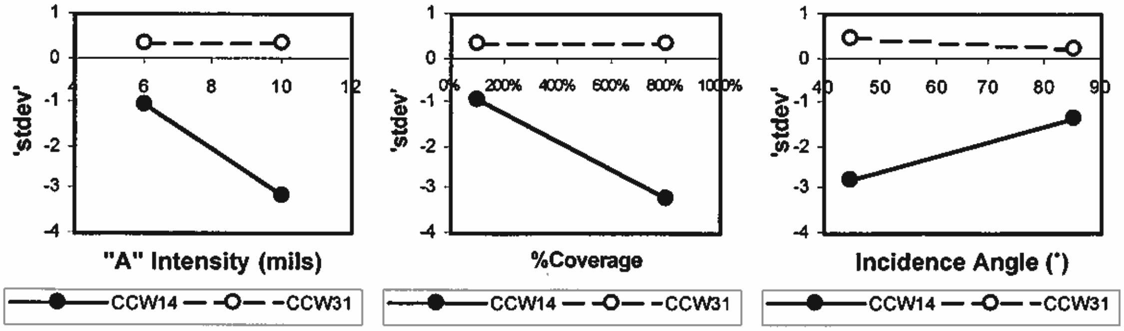
Table 3 – ANOVA Summary of Shot Peen DOE Results

Main Effects & Interactions which are significant at the 95% confidence level. Normalized lives analyzed. Arcsine transformation used to reduce scatter in residuals: arcsine(stdev/6).

#	Factor	Pr > F
1	shot	0.0001
2	shot x coverage	0.0003
3	coverage	0.0005
4	shot x intensity	0.0015
5	intensity	0.0018
6	shot x incidence angle	0.0038
7	incidence angle	0.0161
8	shot x intensity x angle x coverage	0.0446
9	intensity x angle x coverage	0.0498

When multiple factor interactions become significant, this indicates that one or more of the factors does not produce the same trend in life behavior over all levels of the other factors. This is illustrated in the two-way interaction plots in Figure 2 (a)-(c).

From Figure 2, it is quickly seen that the ccw31 shot produced uniformly good life results over the range of peening conditions evaluated by the study. A range of life behaviors was observed for the smaller ccw14 shot, and the eight ccw14 DOE conditions were grouped into three categories for further analysis, as summarized in Table 4.



a) Intensity x Shot Interaction b) Coverage x Shot Interaction c) Angle x Shot Interaction

Figure 2 – Plots of Significant Two-Way Interactions from DOE

Table 4 – Grouping of CCW14 DOE Conditions by Life Behavior

Group	"stdev" Range	Peening Condition
A "Good" life results	0.03 < stdev < 0.55	1) ccw14/6A/45°/100% 3) ccw14/6A/85°/100%
B "Transition" cases	-3 < stdev < -2 surface 0.16 < stdev < 0.29 internal	4) ccw14/6A/85°/800% 7) ccw14/10A/85°/100%
C "Low" life results	-4.23 < stdev < -3.0	2) ccw14/6A/45°/800% 5) ccw14/10A/45°/100% 6) ccw14/10A/45°/800% 8) ccw14/10A/85°/800%

Weibull Analysis of Shot Peen DoE Results.

A Weibull analysis was also conducted, as illustrated in Figure 3. For this analysis, all the ccw31 data points were analyzed together as one group. The ccw14 data points were grouped into three groups, as characterized by their life behavior and identified in Table 4. In addition, the results from four light peening conditions, ccw14/12N/45° and 400-800% coverage were included as a separate population for comparison. A reference curve showing the behavior of comparable low stress grind specimen data is also presented in Figure 3.

The cumulative distribution function for the Weibull distribution [7] is given as:

$$F(t) = 1 - e^{-[(t-t_0)/\eta]^{\beta}} \qquad (2)$$

where t is the life, t_0 is a threshold parameter which applies only to a three-parameter Weibull, β is the shape parameter and η is the scale parameter.

Table 5 gives a summary of the two parameter Weibull analysis results for all populations analyzed. The slope factor from the Weibull analysis can be used to indicate the type of failure mode (slope <1 = infant mortality, slope=1 ⇒ random, slope=2-3⇒ LCF, slope>5⇒ rapid wear out). The 50% line gives the average life. The average lives for the peened ccw31 specimens are not significantly different from low stress ground specimens, but the slopes are much steeper (indicating rapid wear out mode), thereby resulting in lower variation (and higher -3σ lives). An interpretation is that shot peening reduces the crack initiation time (by accumulating plastic strain, which is equivalent to fatigue damage); however it also increases the crack propagation life due to the beneficial residual stress layer imparted. This is another way of describing the effects of competing mechanisms of beneficial residual stresses vs. detrimental plastic strain. Population "A" – ccw14, good lives – has a curve comparable to the ccw31 population.

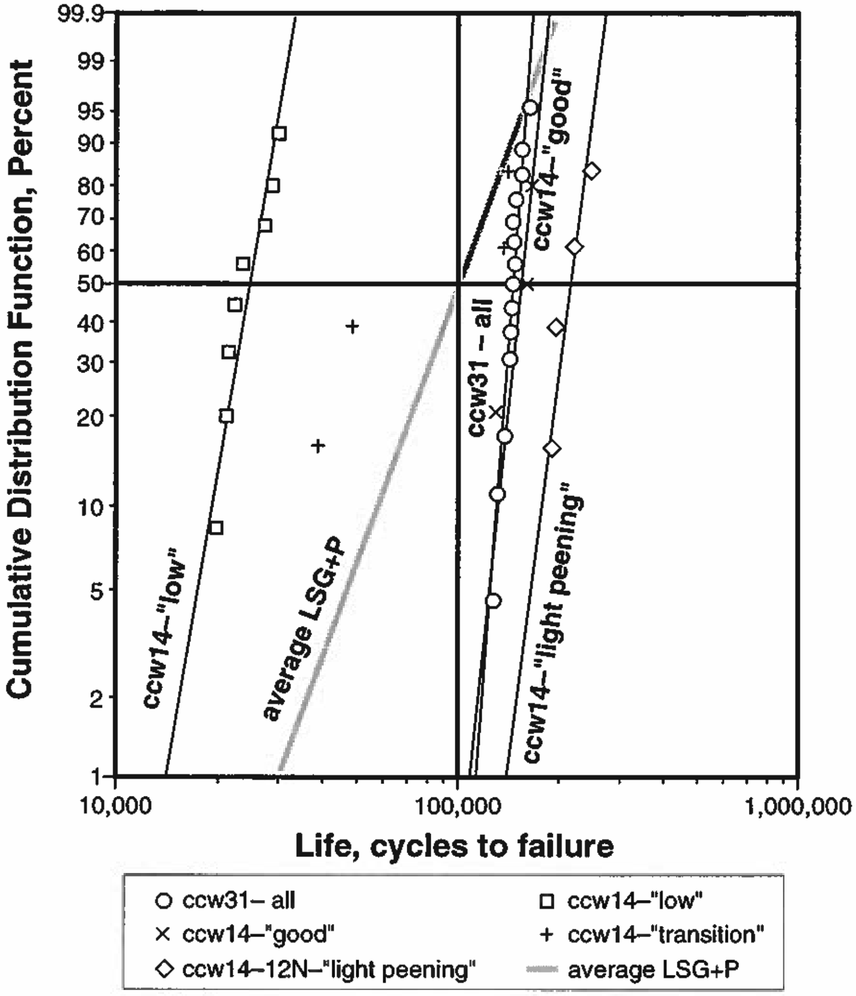


Figure 3 – Weibull Analysis Results (1000°F, stress level chosen to give approx. 100,000 cycle nominal life.)

Table 5 – Two Parameter Weibull Analysis Results of Shot Peen DOE data

symbol	shot	group	SCALE	SHAPE (failure mode)	Interpretation of SHAPE factor	SCALE std. error	SHAPE std. error
× ×	CCW14	A– good	155,845	12.80	rapid wear out	7,352	6.51
+ +	CCW14	B – transition	102,808	2.13	LCF (mixed modes)	25,489	0.89
□ □	CCW14	C – low	25,891	7.71	rapid wear out	1,259	2.12
○ ○	**CCW31**	D – all	146,672	17.48	rapid wear out	2,302	3.15
◇ ◇	CCW14	E – light pn.	220,353	10.01	rapid wear out	11,696	3.79

The ccw14 population "C" - "low" lives - shows a similarly steep slope, but the curve is shifted to the left by nearly one order of magnitude. Thus, more damage is accumulated leaving less crack nucleation life remaining. The fit obtained for the population "B" - the transition in mechanisms group – is poor and reflects the high amount of variability in lives for these specimens. This population contains 2 test results at each of 2 different conditions. There was a large amount of scatter in the test results at each condition, which could be an indication that some type of threshold phenomena is involved.

The ccw14 population "A" - good lives (3 points) - is virtually indistinguishable from the ccw31 curve. The ccw14 - 12N light peened curve is further to the right, suggesting that light peening does even less "detrimental plastic strain damage" resulting in higher average lives in the absence of any surface inclusions. There is other data which suggests that "light peening" does not provide the same level of protection when a surface inclusion is present. More work is needed to understand the limits of light peening in the presence of inclusions.

The results of a three-parameter Weibull analysis performed on the ccw31 data is summarized in Table 6 and shows a negative t_0 (threshold) value. If this analysis is valid, it indicates that a significant amount of the total life capability (about 70%) is consumed by peening; however because of the beneficial effects of the residual stresses, the total life capability is increased by ~480% over low stress ground and polished (LSG+P) specimens. The net effect is an average life which is slightly higher than that of average LSG+P specimens (146,000 vs. 100,000). The three-parameter Weibull analysis is a non-linear analysis and requires a minimum of about 14 data points to yield significant results. It appears to be sensitive to initial values used to start the parameter estimates, so it is possible to find either positive or negative solutions with varying goodness-of-fit characteristics. The analysis conducted resulted in a perfect R^2 regression correlation coefficient of 1. The interpretation of the negative t_0 parameter is consistent with the idea of cold work processes generating the equivalent of fatigue damage.

Table 6 – Three Parameter Weibull Analysis Results of CCW31 data

symbol	shot	Threshold	SCALE	SHAPE	Interpretation	R^2
○ ○	CCW31	-333,308	479,694	71.45	Significant damage (due to shot peening) accumulated prior to test.	1.0

SUMMARY AND CONCLUSIONS:

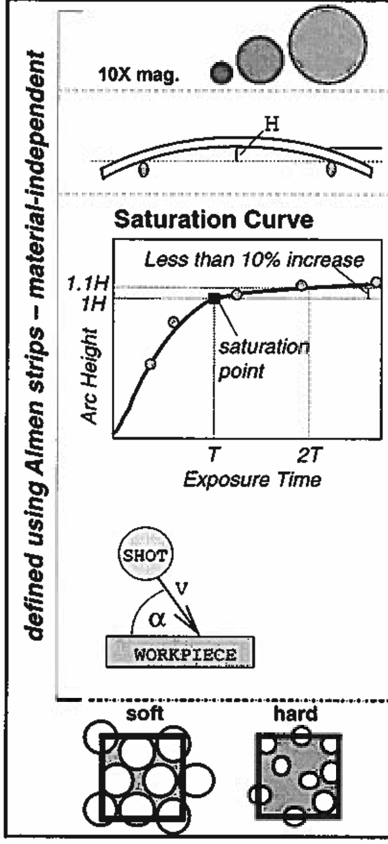
Shot size was extremely significant to life capability obtained over the range of conditions evaluated. For the smaller ccw14 shot size, coverage, intensity and incidence angle were also significant to the life capability obtained. Since peening intensity (independent of shot size, incidence angle or coverage) typically correlates with residual stress profile depth observed, this suggests that the residual stress state is not the primary factor driving the changes in life behavior observed in these cases. Physics suggests that velocity and/or strain rate are key parameters that characterize the impact process, yet these cannot be routinely measured or controlled. Instead, Almen intensity is used to characterize the peening process, along with coverage and saturation. A consistent definition of the basic shot peen process parameters is needed before proceeding further (see Appendix.)

Additional work was needed to understand the physical mechanisms responsible for the change in life behavior observed. This is covered in the following two papers.

The current industry definition of intensity lacks precision needed for improved process control, and does not capture essential elements contributing to life capability. The ability to measure shot velocity would be a valuable addition to process controls for applications where fatigue life capability is important.

APPENDIX:
BASIC SHOT PEENING TERMS AND PROCESS CONTROL PARAMETERS

Six process parameters are used to describe a shot peening condition, as illustrated in Figure 4: 1) Shot (type and size), 2) Intensity, 3) Saturation, 4) Incidence Angle, 5) Velocity, and 6) Coverage. These parameters are independent of the type of shot peening machine used. Of these parameters, only shot type and incidence angle are controlled directly (and there is still considerable variation within these). The remaining parameters are measured or evaluated, in most cases after peening is complete. Peening machine parameters such as hose diameter, air pressure, shot mass flow rate, nozzle type, feed rate of nozzle along workpiece, distance of nozzle from workpiece and workpiece table speed (in revolutions per minute) are controlled and adjusted to obtain desired values of intensity, saturation and coverage. Reliable velocity measurements during the peening process have been difficult to achieve. Because of this, velocity has not been used traditionally as a process control.



Shot sizes:	**ccw14** (0.014 inches ϕ) **ccw31** (0.031inches ϕ) **ccw52** (0.052 inches ϕ)
Intensity:	related to **strain energy** transferred during peening. Defined by the arc height deflection of thin metal "Almen" strips, in mils, at a reference saturation condition.
Saturation:	"Saturation" is used to describe the accumulation of dimples on the Almen strip surface such that plastic strain or work hardening is fairly uniform. It is often used interchangeably with the term "coverage." Because the arc height deflection of an Almen strip depends on the saturation or accumulation of dimples on the surface, a **Saturation Curve** is needed to define **intensity** at a **reference saturation condition**. The saturation point is defined as the point on the saturation curve for which a doubling of exposure time results in less than a 10% increase in arc height. Because this is not a unique definition, variation may be observed in specimens peened by different vendors, or operators.
Incidence Angle:	angle of impact from workpiece surface (α) Higher incidence angles are less damaging, and result in less erosion. *(Lower velocities needed to achieve desired intensity, also less frictional heating at impact.)*
Velocity:	Velocity of shot at the workpiece (V), together with shot size, shape, density and incidence angle probably controls the intensity-saturation curve behavior.
% coverage:	describes % of surface covered by dimples. This is material-dependent: softer materials will cover faster⇒ larger dimples. The two squares at left represent different materials peened at the same intensity / saturation condition.

Figure 4 – Basic Shot Peening Terms

<u>Shot</u>. For the purposes of this investigation, conditioned cut-wire shot was used in two sizes: ccw14 (~.014 inch diameter particles) and ccw31 (~.031 inch diameter particles).

<u>Intensity</u>. The shot peen intensity is not a simply defined parameter [8]. It represents a measure of strain energy transferred to thin metal "Almen" strips, fabricated from SAE 1070 carbon steel. Measurements of the arc height deflection of Almen strips are made for various exposure times and plotted on a saturation curve as shown in Figure 4. As more dimples accumulate on the surface, greater bending is observed and the arc height increases. The intensity is defined as that point on the saturation curve for which a doubling of the exposure time results in less than a 10% increase in arc height [8]. It appears that the intent of the definition is to ensure that the intensity reading is obtained on a point to the right of the knee of the saturation curve, where changes in exposure time provide relatively little change in arc height. However, this is not a unique definition. Intensity measurements taken using this approach can result in confounding of the effects of coverage or saturation, shot velocity and shot size. This can lead to conflicting observations.

For example, Niku-Lari [2] notes that the "multiplicity of parameters makes the precise control and repeatability of a shot-peening operation very problematical." Niku-Lari obtained very different depths of plastic deformation layer corresponding to identical Almen deflection measurements. He concluded that very different distributions of residual stresses could be obtained for the same Almen deflection measurement. Note that a single Almen deflection measurement alone does not define the intensity. In contrast, Fuchs [9] observed a nearly linear relationship between the depth of compressive stress and Almen intensity from his experimental data. Linear regression analysis of earlier residual stress data taken from coupons of René 88DT peened with ccw14 and ccw31 shot found the depth of compressive stress layer to be a nearly linear function of intensity, supporting Fuchs' observation.

Three thicknesses of Almen strips are used: N (thinnest), A, C (thickest). In the United States, the deflections are typically quoted in mils (0.001 inches) thus 6A intensity represents 0.006 inches arc height deflection of an Almen "A" strip. In Europe, metric measurements are used. Unfortunately the peening literature tends to lack rigor in reporting intensity measurements. It is common to see intensities of 2A or 4A without an explicit statement of scale. In addition, a general lack of awareness of the variability encountered in applying the intensity definition can lead to inconsistent interpretation of intensity across the range of people and companies involved with shot peening. Almen Strip variability also contributes to uncertainty in intensity measurements, as reported by Happ and Rumpf [10]. These factors make it difficult to compare peening conditions, results and conclusions across various papers with confidence. Kirk [11] has done some work on a device that would provide interactive control of shot peening intensity which could alleviate some of these problems.

Saturation & Coverage. The terms saturation and coverage are often interchanged. Both deal with the accumulation of dimples on the target surface. Strictly speaking, 100% saturation refers to a point on a saturation curve (see Figure 4), for which a doubling of the exposure time will result in less than a 10% increase in Almen strip arc height. Coverage describes the physical covering of the surface by dimples, and is usually estimated by a visual inspection. Because the deflection of the Almen strip levels off with increasing exposure after ~100% coverage has been achieved, both terms characterize a similar physical event, although the saturation point does not correspond to 100% coverage [12]. Lombardo and Bailey [12] and Abyaneh [13] demonstrated that accumulation of surface coverage results in a curve having the form of the Avrami equation, which also characterizes the saturation behavior. Since saturation is defined only on Almen strips, it applies only to "coverage" of Almen strips, and is independent of the workpiece material to be peened. Because the intensity definition does not result in a unique peening condition, it is fairly common for the "100% saturation" point to be selected by a visual inspection of a peened Almen Strip surface for approximately complete dimple coverage. Additional peening conditions are then selected to complete a saturation curve. If "T" represents "100% saturation", then typically three additional points, corresponding to 0.5T, 2T and 4T points will be run. If the arc height at the 2T condition is less than 1.1 times the arc height at the 1T condition, then the 1T point is accepted as a valid 100% saturation condition. However, more or less exposure time may be required to achieve a visual 100% coverage on the workpiece. Softer materials will cover faster than hard materials (see Figure 4). "800%" coverage is achieved by peening each specimen 8 times longer than that necessary for 100% coverage.

Incidence angle is the angle between the target surface and direction of incoming shot. Thus, 90° represents a normal impact (perpendicular to the surface) and 45° represents an oblique impact. For a desired intensity, required velocity is minimized for 90° incidence angles. Oblique incidence angles require higher shot velocities to attain a given intensity.

Velocity of the shot is one of the most important physical parameters characterizing the impact event [2]. It appears that the component of velocity normal to the workpiece surface controls the shot peening intensity. Since intensity is a measure of strain energy induced, small shot must travel at significantly higher velocities than larger shot to achieve the same intensity. Since strain rate can be estimated as the impact velocity divided by the shot radius, high velocities also mean high strain rates. For the particle sizes typically used to peen aircraft engine components, strain rates can exceed 5E+05 1/sec for small shot.

Due to the difficulty of measuring shot velocity at the workpiece, it has not been used for process control. Recently, laser velocity sensors developed for aerodynamics research have been adapted for use in shot velocity measurements in a lab environment at some locations. Electromagnetic sensors, which use the magnetic properties of steel shot as they pass through an inductance coil, are the other technology that has been used. Each have different limitations. Neither is in widespread use.

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