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Modeling of Fatigue Behavior due to Shot Peening Conditions

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1 Introduction

The beneficial effects of shot peening have long been recognized. One of the major reasons for shot peening is to induce a beneficial surface condition (compressive stress layer and altered microstructure) that acts to retard the development and propagation of surface cracks. If surface crack formation and propagation can be suppressed, longer component operating lives can often be attained. Dörr and Wagner [1] 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 [2], and others have recognized, however, that shot peening can also cause the equivalent of fatigue damage. This effect has received considerably less attention.

There is increasing interest in methods to predict life capability of shot peened parts, and in the use of models that enable a designer to select a robust level of shot peening that will optimize the life benefit, minimize manufacturing costs, and avoid potential life degradation from "overpeening".

This paper examines six different approaches to assessing shot peen impact on life. Four approaches focus on fatigue crack initiation life, or rather the life to failure in the absence of preexisting cracks. One method deals with crack propagation life. The final approach attempts to correlate surface residual stress state with residual life remaining at the time of inspection. Of these six approaches, only two offer general predictive tools: one of fatigue initiation life, the other of crack propagation life. The other methods provide alternate ways for analyzing and using specific fatigue and/or residual stress data.

This paper examines some of the challenges and limitations in using each of these methods. Where possible, these methods are demonstrated using data from a shot peening Design of Experiment (DOE) conducted on Rene' 88DT, a nickel-base superalloy, as documented in references [3, 4, 5, 6].

It must be noted that life prediction methods are engineering attempts at modeling complex physical processes, and will therefore always be limited by inadequate understanding and inability to model the significant elements of physical reality. All models are wrong – by definition they are approximations at best – but some are useful. The most useful are substantiated by data covering the relevant conditions of interest. One must be cautious when trying to apply a model to conditions outside the validated set of conditions – physical reality is often complex and nonlinear, and does not always cooperate with attempts at extrapolation.

2 Challenges and Approaches to Modeling Life Behavior

Perhaps the greatest challenge with any life prediction method is obtaining the data necessary to generate a useful model. Life behavior can be affected by many factors:

- operating conditions ("mission" – including stress & temperature profile, minimum, maximum and mean stresses experienced, and time or duration at specific conditions)
- operating environment (air, vacuum, salt water, etc.)
- geometry (including resulting stress concentrations, stress gradients and stress state)
- surface condition – topography & microstructure (low stress ground & polished, turned, broached, reamed, shot peened, etc. & various combinations; each of these processes may have additional specific parameters which need to be defined in order to adequately characterize the surface state)
- residual stress state (tensile or compressive stress at surface, maximum stress magnitude and depth of residual stress layer)
- material (chemistry, processing method – cast or wrought, heat treatment, microstructure).

A variety of methods are reviewed here. Some are very specific and are able to incorporate the details of operating conditions, geometry, and specific surface condition since they are derived from specific component or test data. Others can be used as more general predictive tools, but will generally result in reduced correlation with specific data since they are not as well adapted to assessing the variety of factors which can affect component life.

2.1 Weibull Analysis of Data at Specific Test Conditions

One life prediction approach is to fit replicate specimen fatigue test data collected at specific test conditions to statistical distribution functions. The Weibull distribution [7] is often used to analyze failure data including analysis of complete systems or components. When used for analysis of actual component failures it is particularly powerful because the specific details of operating conditions, geometry, surface condition & material can be accounted for. The cumulative distribution function is given as:

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

Figure 1 shows the results of a Weibull analysis for 5 different shot peen populations compared against a low stress-grind & polish (LSG+P) baseline [3], while Table 2 summarizes the minimum and median lives for each population. Note that the 50 % line gives the median life. A -3σ life would correspond to a CDF value of 0.135 %. Shot peening behavior observed fell into three categories: 1) good – life benefit, 2) low – life degraded, and 3) transition – some low and high life results at the same peening condition. If one ignores the transition group, all other populations exhibit a high slope characteristic of a "rapid wear out" mode. This suggests 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 surface state imparted.

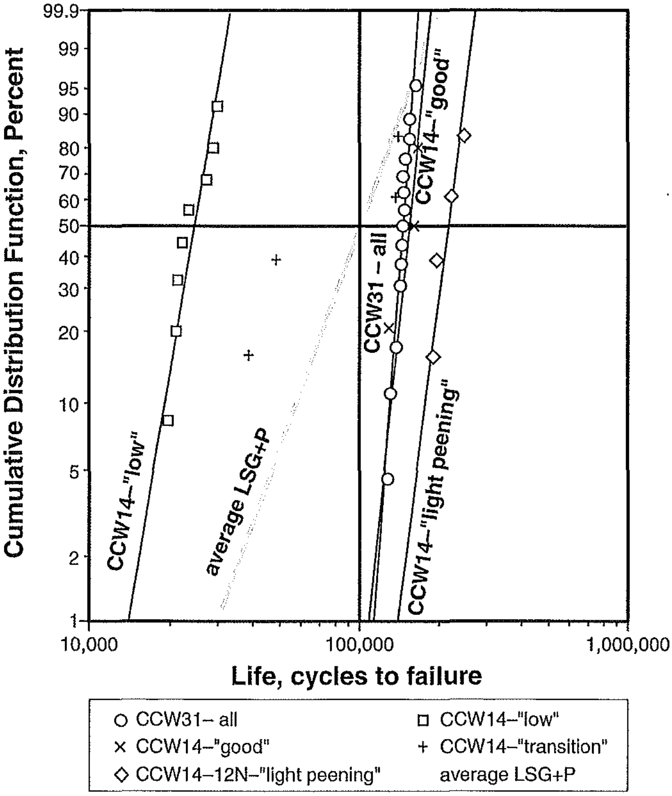


Figure 1: Weibull Analysis Results (1000 °F, stress level chosen to give approx. 100,000 cycle nominal life.)

Table 1: Two parameter Weibull analysis results of shot peen DOE data

symbol	shot	group	SCALE (average life)	SHAPE (failure mode)	Interpretation of SHAPE factor	Minimum Life (~.135 %)	Median Life (~50 %)
×	CCW14	A – good	155,845	12.80	rapid wear out	93,000	151,000
+	CCW14	B – transition	102,808	2.13	LCF (mixed modes)	4,600	87,000
□	CCW14	C – low	25,891	7.71	rapid wear out	11,000	25,000
○	CCW31	D – all	146,672	17.48	rapid wear out	100,500	143,000
◇	CCW14	E – light pn.	220,353	10.01	rapid wear out	114,000	212,000

Compared with LSG+P data, shot peening resulted in tighter scatter of low cycle fatigue results. For shot peening conditions that resulted in "robust" life conditions – groups A, D and E, the increase in the minimum life capability is perhaps more dramatic and significant than the improvements to median life capability. For this particular example, a minimum life of approximately 17,000 cycles would be predicted for LSG+P specimens, and a median life of ~100,000 cycles. By comparison, group D (CCW31 shot peened specimens) resulted in a minimum life of ~100,500 cycles and a median life of 143,000 cycles. However, group C (CCW14, overpeening conditions) resulted in a minimum life of 11,000 cycles and median life of 25,000 cycles.

To summarize, a Weibull analysis can be a powerful tool for evaluating life capability of homogeneous populations. That is, for data sets with similar peening conditions, geometry, operating conditions, etc. Very useful life predictions can be obtained with this approach. The drawback is that very specific data are needed. This is more useful as a field management tool, rather than as a design tool for selecting component shot peening conditions.

2.2 Fatigue Crack Initiation Analysis

Fatigue behavior is often broken down into two phases: fatigue crack initiation and fatigue crack propagation. Initiation assessment often relies on the use of S-N (stress vs. life) curves, generated by statistical analysis of test data for the material of interest over a range of stresses at specific temperatures. A "minimum" life curve is used to establish safe operating limits for critical components whose failure might present a safety concern. However significant changes in process capability can often be assessed by comparing average life behavior. So, both average and minimum life capability are of interest.

Due to the variety of factors affecting fatigue behavior, it is very difficult to come up with a single analytical method to assess life impact due to a variety of shot peening conditions. Fatigue life correlation and comparative assessment can be attempted for specific conditions.

2.2.1 Modified Goodman Formula with Surface Roughness Measurement

A Modified Goodman Formula approach developed by Li, Mei, Duo and Wang [8] provides a fairly general predictive model. This method requires representative surface roughness measurements to formulate an appropriate stress concentration factor (K_t), as well as knowledge of the residual stress state and information about baseline material life behavior. It can be applied only to materials that demonstrate an endurance limit.

Extensive 3D analysis was used to relate a geometric stress concentration factor (K_t) as a function of specific surface roughness parameters, R_t (peak dimple depth) and S (dimple spacing). As a result of this work, an appropriate K_t can be generated for any peening condition for which the appropriate surface roughness parameters can be obtained. Surface roughness measurements are non-destructive and relatively easy to obtain.

Finally, a modified Goodman formula was used to predict life, incorporating the residual stresses as a mean stress effect and the K_t as a stress multiplier. The Goodman relation can only be used for materials that exhibit a fatigue strength. Not all materials exhibit this behavior. Further, it is not clear whether this method works over a wide range of peening conditions, from damaging to beneficial. Since Rene' 88DT does not exhibit a fatigue strength, it was not possible to apply this method to the reference data set documented in references [3-6].

2.3 Analyzing Fatigue Data to Define Robust Process Windows

In some cases, the goal is not to quantify the life capability due to shot peening, but to ensure that the process window defined for a particular component is robust and does not result in degraded life capability. Designed Experiments and Damage Maps are two methods that have been used as simple models to identify parameter settings which result in acceptable life behavior.

2.3.1 Analysis of Variation (ANOVA) Approach

Although less useful as a predictive fatigue life model, designed experiments (also called DOE's) using ANOVA methods can be used to evaluate life impact due to a variety of process conditions at a selected test condition. In fact, the strength of these methods is in their ability to efficiently identify the few significant factors from the many potential factors. However, resources are generally limited and are therefore focused on assessing the process parameters at an operating condition selected to meet design needs. So, the goal is normally to define and validate a robust process window, not to develop and validate a life prediction tool over the range of operating conditions that a component might see in actual operation.

For analysis of life capability as a function of various process parameters, the use of a normalized life parameter, "stdev" can be very useful:

$$stdev = \frac{\left[\log\left(N_{obs}\right) - \log\left(N_{avg}\right)\right]}{\left[\log\left(N_{avg}\right) - \log\left(N_{-3\sigma}\right)\right]/3} \tag{2}$$

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

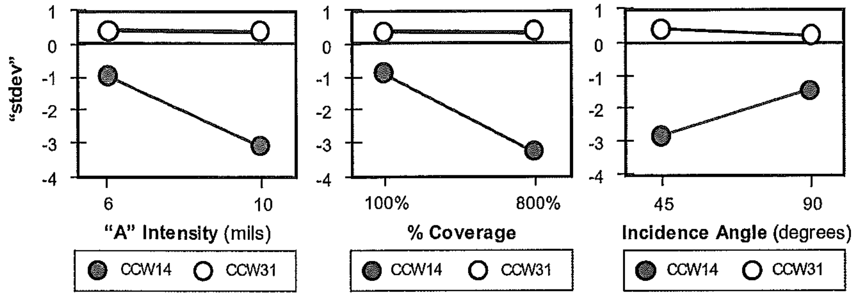
Table 2 summarizes the significant factors identified by the Rene' 88 DT study [3]. The DOE data provide evidence of significant interactions between peening parameters. A total of nine effects, including all four main effects, 3/6 two-way interactions, 1/4 three-way interactions and the single four-way interaction were found to be significant at the 95 % confidence level.

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), using the normalized life parameter, 'stdev'. From these plots, it can quickly be seen that CCW31 shot produced uniformly good life results over the range of peening conditions evaluated by the study. By comparison, intensity, % coverage and incidence angle all exhibited significant impact on life capability of specimens peened with smaller CCW14 shot.

Table 2: ANOVA summary of shot peen DOE results

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

Main Effects & Interactions which are significant at the 95 % confidence level. ($Pr < 0.05$ are significant.) Normalized lives analyzed. Arcsine transformation used to reduce scatter in residuals: arcsine(stdev/6).



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. 'stdev' plotted on Y axis

Although many factors were identified as being significant to life behavior, this analysis does not shed any light on the physics behind the behavior. Results from a separate investigation [4, 5, 6] suggest that shot velocity is a critical physical parameter which can trigger a change in life behavior for Rene' 88DT. Unfortunately, shot velocity measurements are difficult to make and are not a standard part of the shot peening process controls used today. But this illustrates the potential for lurking variables that cannot be directly controlled or evaluated in some DOE's.

2.3.2 Damage Map Approach

Designed experiments permit powerful and efficient statistical analysis of the data. However, they require planned experiment designs. "Messy" or "happenstance" data can not be analyzed using ANOVA methods. An alternative is to plot the data as a function of the parameters of interest, using symbols to distinguish "good", "neutral" or "low" life behavior. Figure 3 shows an example.

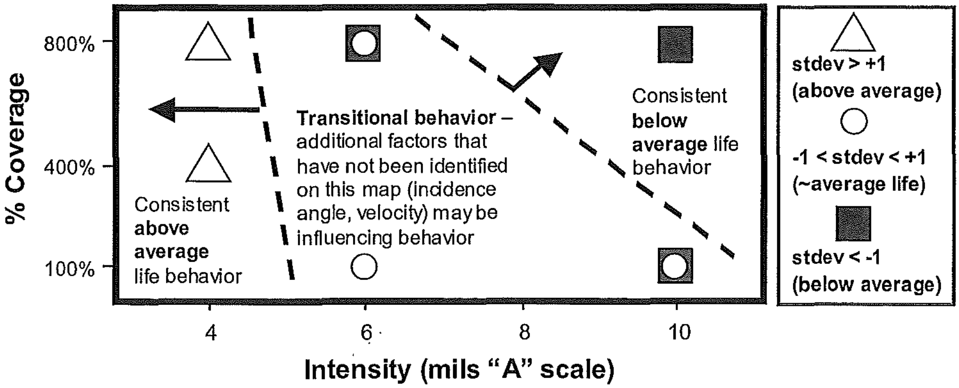


Figure 3: Damage map illustrating interpretation of CCW14 data from DOE [4]

It is easier to miss significant factors using this approach. However, it can be used to help evaluate messy or happenstance data, and to select test conditions of interest for future designed experiments.

2.4 Predicting Peened Surface Fatigue Crack Propagation Behavior

Fracture mechanics (FM) is a well-established discipline that enables life predictions when initial cracks are known to exist. The effect of shot peening can be incorporated into FM analysis by modeling the residual stress profile and using the principles of linear superposition via Green's functions. This affects the mean stress intensity factor. It is important to calibrate the predictions against test results to better account for stress relaxation effects due to thermal and cyclic loading.

Residual stresses are readily measured using x-ray diffraction techniques. If desired, the raw data can be curve-fit to provide a more continuous definition. A functional form that appears to work well for many materials, is shown in equation (3) and illustrated in Figure 4.

$$\sigma_{RS}(x) = A \cdot \exp[-x/\lambda] \cdot \sin(B \cdot x + C) \tag{3}$$

Prior work shows that the depth of the compressive stress layer is nearly a linear function of shot peen intensity [6]. Variations in shot peen process parameters which result in significant changes to residual stress profiles can be accounted for in a FM analysis by modeling the different profiles. FM calculations using a variety of Rene' 88DT shot peen profiles showed very minor differences for small changes in intensity, or variations of incidence angle and % coverage over a small intensity range. For example, data from 6 to 8A peening conditions could be regressed as one population. Data from 6 to 12N could also be regressed as a single population, having a slightly different benefit than a 6-8A model.

FM provides a general predictive tool that is appropriate when pre-existing cracks are known to exist, and for assessments that assume the presence of an initial crack. It is capable of mode-

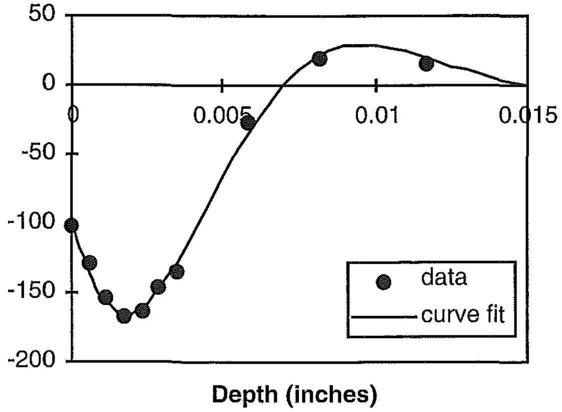


Figure 4: Sample residual stress profile and corresponding curve fit, peening condition: CCW31 shot, 6A intensity, 45 degree incidence angle, 800 % coverage

ling complex stress & temperature missions, as well as a variety of stress gradients, component and crack geometries.

2.5 Residual Life Prediction as a Function of Surface Residual Stress

Bradley, Berkley, and Fairbank [9], and Berkley [10] describe the use of surface residual stress measurements (taken non-destructively using x-ray diffraction) to correlate with residual life of aircraft engine components. This work is still in the development stages. This approach assumes that the component surface is initially in a state of compression, due to shot peening or other surface treatment, and that the residual stress condition of the component declines toward tension with service cycles and / or hours.

One of the concerns with this approach is that x-ray diffraction surface residual stress measurements show a high level of variation. They are also subject to errors caused by the presence of a sub-surface stress gradient as well as difficulties in interpreting surface results [11].

Another question is whether the surface stress relaxation is significant, and correlates with % life consumed. Figure 5 shows some normalized near surface residual stress profiles that have experienced static thermal exposure or cycling at elevated temperature. Figures 5a-c were taken from specimens made from Rene' 88DT, a nickel-base superalloy, while 5d profiles were taken from Marage 250, a steel.

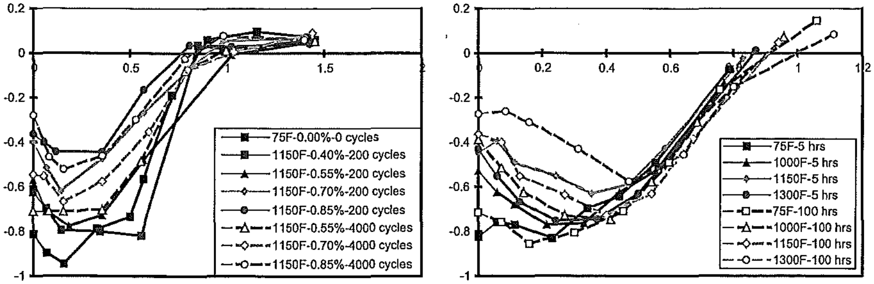
Figure 5a shows that progressive relaxation occurs as strain range is increased at a given temperature on Rene' 88DT. No clear trend of relaxation as a function of cycles was observed. In fact, compressive residual stresses increased slightly for some cases. This is probably within the normal scatter of residual stress measurements for this peening condition.

Figure 5b shows that progressive relaxation of residual stresses also occurs with increasing temperature for Rene' 88DT, even in the absence of cyclic loading. A greater difference in relaxation behavior was observed as a function of time at 1300 F than was observed at lower temperatures. As it appears that thermal exposure can accomplish the same amount of surface stress relaxation as cyclic loading without any consumption of life, this should complicate the use of surface residual stress as a reliable correlation to residual life.

Figure 5c shows residual stress profiles taken from LCF specimens after failure. These specimens were all peened to the same damaging shot peening condition. Two specimens had small amounts of the damaged surface layer removed by electropolishing. All three specimens were then cycled to failure. Residual stress measurements were taken on the remaining gage section a small distance away from the fracture surface. Although surface residual stresses did go tensile for the two electropolished specimens, the third specimen exhibited compression on the surface even after failure. This suggests that surface residual stress may not be a reliable or robust indicator of residual fatigue life.

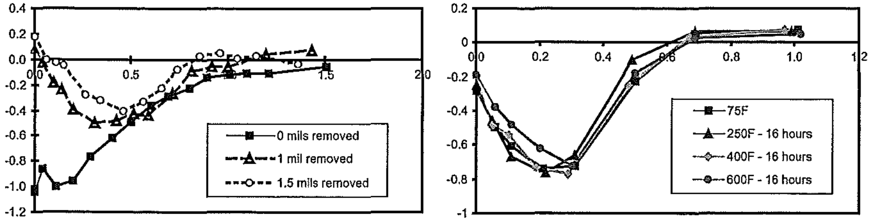
Finally, Figure 5d illustrates the thermal stability of residual stress profiles in Marage 250 as a function of thermal exposure temperature. Unlike Rene' 88DT, very little variation in residual stress profiles was observed over a range of temperatures and peening conditions. This demonstrates the importance of obtaining data for the specific material, shot peening conditions and operating conditions of interest.

Although this methodology would provide a unique approach to damage monitoring, there are several questions about the robustness and general applicability of the approach. It appears that much more validation is needed.



a) Rene' 88DT: CCW31 – 7A/45/100% - 200 to 4000 cycles at 1150F

b) Rene' 88DT: CCW31 – 7A/45/100% - 5 to 100 hours thermal exposure



c) Rene' 88DT: CCW14 – 10A/45/800% - cycled to failure

d) Marage 250: S110 – 10A/45/800% - 16 hours thermal exposure

Figure 5: Normalized residual stress profiles illustrating the effects of a variety of thermal exposure & cyclic loading conditions. Stress (Y axis) normalized by reference stress. Depth (X axis) normalized by shot peen intensity.

3 Conclusions

There presently appears no single robust process for fatigue life prediction of shot peened components, nor is development likely, given the differences in material behavior and ranges of use. However there are a number of approaches and tools that can be used to assess the influence of peening on life, depending on the specific need. All methods and tools rely heavily on test data to generate the model elements and/or validate their use.

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