The Effect of Shot Peening Coverage on Residual Stress, Cold Work and Fatigue in a Ni-Cr-Mo Low Alloy Steel

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Introduction

The underlying motivation for this work was to test the conventional wisdom that 100% coverage by shot peening is required to achieve full benefit in terms of compressive residual stress magnitude and depth as well as fatigue strength. Fatigue performance of many shot peened alloys is widely reported to increase with coverage up to 100%, by many investigators and even in shot peening manuals.(1) The fatigue strength of some alloys is reported to be reduced by excessive coverage(2) Aerospace(3,4), automotive(5), and military(6) shot peening specifications require at least 100% coverage. Internal shot peening procedures of aerospace manufacturers may require 125% to 200% coverage. Most of the published fatigue data supporting the 100% minimum coverage recommendation was developed in fully reversed axial loading(2,7) or bending(8,9) with a stress ratio, $R = S_{min} / S_{max}$, of –1.

The residual stress field arising from an individual shot impact is much greater in extent than the physical size of the impact crater and the resulting surrounding ridge of raised material.(10) Hence, at least some degree of undimpled surface area, less than 100% coverage, should be tolerable in terms of residual stress and fatigue strength achieved by peening. Accordingly, residual stress-depth distributions were determined for specimens peened to various coverage levels. Fatigue performance was tested at R>0, so that the shot peened surface was loaded only in tension. Additionally, cold work-depth distributions and the effects of thermal relaxation on both residual stresses and cold work were determined.

Material

Aircraft quality 4340 steel plate (0.5 in. thick) per AMS 6359F(11) was employed in this work. The material composition is provided in Table 1 below.

Table 1
Steel Composition

C	Mn	P	S	Si	Cr	Ni	Mo
0.40	0.68	0.015	0.015	0.23	0.79	1.70	0.23

For peening trials, specimens about 33 x 38 mm (1.3 x 1.5 in.) were cut from the plate with the longer dimension oriented along the rolling direction. After hardening and tempering to 38 HRC hardness, specimens were reduced to 9.5 mm (0.375-in.) thickness by low stress grinding. Tensile properties resulting from heat treatment were 1164 MPa (169 ksi) ultimate tensile strength and 1089 MPa (158 ksi) 0.2% offset yield strength.

Experimental Procedures

Shot Peening

Peening was performed via direct air pressure at 482 kPa (70 psi.) through a single 4.7 mm (3/16-in.) diameter nozzle aligned to give an 80-degree incidence angle from horizontal. Specimens were mounted on a rotary table running at 6 RPM at a vertical distance of 305 mm (12 in.) from the nozzle outlet. Carbon steel CCW14 conditioned cut wire shot was used at a controlled flow rate of 1.36 kg/min (3 lb./min). The intensity achieved was 0.22 mmA (0.009 in.A). Coverage was determined by optical observation at 20X magnification. The time to achieve 100% coverage was taken as the peening exposure time at which essentially no undimpled areas remained in an approximately 2.5 cm (1.0 in.) square area in the center of specimens. Undimpled areas were easily observed via surface texture contrast between the original ground surface and shot impacted areas. Fractional and multiple coverages were then taken appropriately as ratios of the time for 100% coverage.

Coverage is defined in the shot peening literature both in terms of the fraction of area impacted, as used here, and as multiples of the time required to achieve saturation of the Almen strip. The saturation-based definition does not include the effects of the work piece properties, such as hardness and yield strength, which influence dimple diameter and the total area impacted. Assessing coverage as the fraction of the area impacted using optical examination is inherently subjective, but does include the effect of the work piece mechanical properties, and is the method adopted by most shot peening standards.(3,4,5,6) In this study, 100% area coverage was achieved in 5.0 minutes (intermittent peening on the turn table) while only 2.0 minutes was required for saturation of the Almen strip under the same peening conditions; a factor of 2.5 difference between the two coverage definitions. To avoid ambiguity, the number of shot impacting the sample per mm^2 at 100% coverage was quantified by direct measurement of total collected shot as 336 shot/mm^2. The coverage calculated from the dimple diameter and total impacts(12) was 99.8%.

Residual Stress and Cold Work Determinations

Residual stress measurements were made via x-ray diffraction in the conventional manner from the shift in (211) diffraction peak position using Cr Kα radiation.(13,14,15) Subsurface data were obtained using automated residual stress profiling apparatus to alternately measure the residual stress and then electropolish to remove layers.(16) Residual stress measurements made as a function of depth from the peened surface were corrected for relief resulting from layer removal and for penetration of the x-ray beam into the subsurface stress gradient. An irradiate area of nominally 5 x 5 mm (0.2 x 0.2 in.) was used for residual stress measurement, providing the arithmetic average residual stress over the area of an estimated 8400 shot impacts at 100% coverage.

Determinations of cold work resulting from peening were made by relating (211) diffraction peak breadths to the equivalent true plastic strains.(17) The distribution of cold work as a function of depth was thus obtained from diffraction peak breadth measurements made simultaneously with residual stress measurements.

Thermal Relaxation

Following residual stress and cold work determinations, specimens were thermally exposed at 519K (475F) for 24 hours. Residual stress and cold work determinations were then repeated to determine if thermally induced relaxation had occurred.

High Cycle Fatigue Testing

Fatigue testing in four-point bending mode was conducted at room temperature under constant load amplitude sinusoidal loading at 30 Hz and stress ratio, R, of 0.1. The R-ratio was chosen to avoid compressive overload and the immediate reduction of the compression introduced by shot peening. Bending fatigue specimens were machined with a trapezoidal cross section to ensure fatigue failure from the peened surfaces. The specimen geometry and test fixturing provided a nominally 0.5-in. wide by 1-in. long surface area under uniform applied stress. The central gage sections of fatigue specimen test surfaces were finished by low stress grinding and peening using the same techniques as for specimens in peening coverage trials.

Results and Discussion

Coverage

Figure 1 provides representative photographs of surfaces peened to various coverages. Not included in the scope of this study was determination, by area measurement, of the actual percentage of dimpled surface area for various peening times. In the context of this work, it sufficed to define coverage based upon the time ratio to achieve 100% dimpling of the surface area. As one may infer from the photographs, the percent of area covered at 0.8T approached that at T. The arrow in the photograph for 0.8T indicates a very small undimpled area easily visible when viewed optically at 20X magnification. Undimpled areas in specimens peened for times less than 0.8T are obvious in appearance as they appear in Figure 1. The overall appearance of surfaces peened for times, 2T and 4T, did not change relative to that peened for time, T.

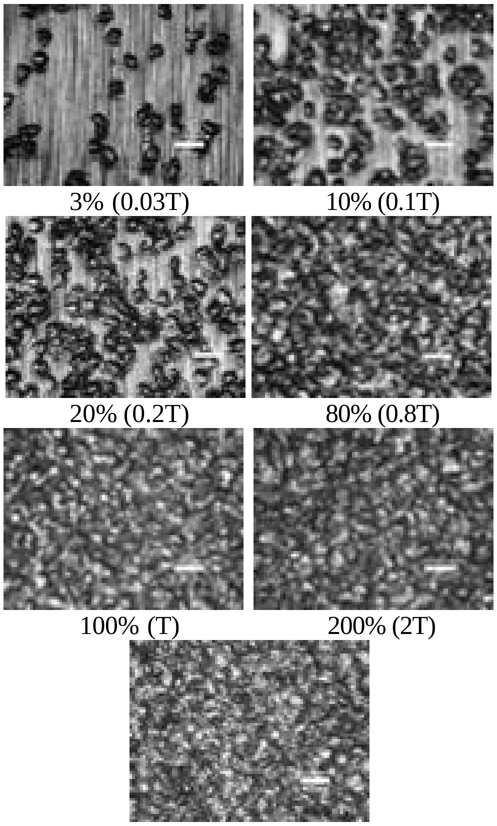
3% (0.03T) 10% (0.1T)
20% (0.2T) 80% (0.8T)
100% (T) 200% (2T)
400% (4T)

Figure 1. Surfaces peened to various coverage levels (ratio of time for 100% coverage) *The small white bar in each photograph represents 0.25 mm (0.01 in.)*

Residual Stress Distributions

Figure 2 shows residual stress-depth distributions for various coverage levels, including the distribution for the as-ground surface before peening. Except at the lowest coverage level, 3% (0.03T), classical shot peening distributions resulted, whereby residual compressive stress magnitudes reached a subsurface maximum and decreased gradually until small tensile stresses occurred at greater depths. For 3% coverage, the maximum compression occurred either at the surface or at a very slight depth not resolved in the series of measurements taken. The form of the subsurface residual stress distribution for 3% coverage conforms to finite element models of the stress developed in regions between dimples when impact areas are widely separated by twice the dimple radius.(21) Given that the x-ray diffraction results provide an average stress over mostly un-impacted material at the 3% coverage, the data appear to confirm the FE prediction that even the regions between impacts are in compression. The distributions for coverage levels less than 20% (0.2T) exhibited systematic changes with coverage, whereby increasing coverage in this range resulted in increasing compressive stress magnitude at given subsurface depths and an increase in the total depth of compression. Beyond 20% coverage, there were no further significant changes in stress magnitude at a given depth, other than at the surface, or in total depth of compression. Compression at the surface tended to decrease with increasing coverage above 20%.

Cold Work Distributions

Figure 3 shows cold work-depth distributions produced at various coverage levels. Consistent with residual stress-depth distributions, systematic changes in cold work-depth distributions occurred with increasing coverage level up to 20% (0.02T). Beyond that level, no systematic changes occurred with increasing coverage. Cold work values for the lower coverage levels were lower than at higher coverages only to a depth of about 0.05 mm (0.002 in.).

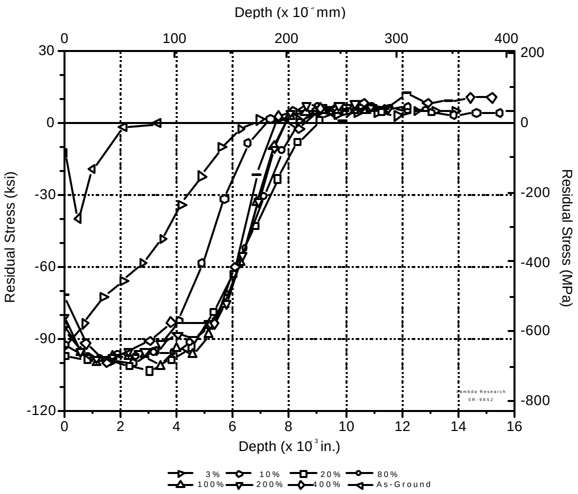

Figure 2. Residual stress-depth distributions for various coverage levels. *Coverage is defined as the ratio of time to produce 100% surface impacts.*

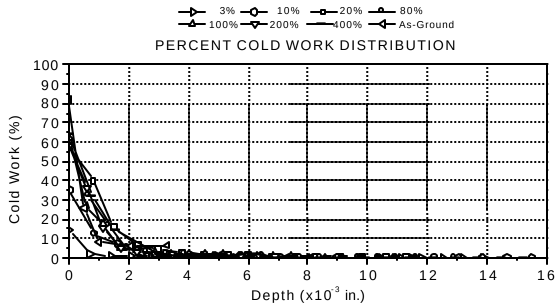

Figure 3. Cold work-depth distributions for various coverage levels
Coverage is defined as ratio of time to produce 100% surface impacts.

Thermal Relaxation

Figures 4 and 5 show the residual stress and cold work depth distributions obtained after thermal exposure at 519K (475F) for 24 hours. This exposure temperature was chosen based upon specification, AMS 13165(4), regarding maximum recommended exposure temperature to avoid residual stress relaxation in shot peened steels. Comparison with pre-exposure results (Figures 2 and 3) revealed changes in both residual stress magnitudes and cold work. Relaxation of both residual stress and cold work occurred at depths less than 0.05 mm (0.002 in.) with the greatest percent changes occurring in surface values. Reduction of surface residual stress magnitudes ranged from 20-30%, and percent reduction of surface cold work ranged from 40-70%. There was no systematic trend with coverage in these reductions although the reductions decreased with depth from the surface, and initial cold work level, to about 0.05 mm (0.002 in.) for all coverage levels. Beyond 0.05 mm depth, where the initial cold work level was less than nominally 5%, there were no significant changes in residual stress or cold work.

These observations highlight the importance of cold work in residual stress relaxation as has been observed in previous studies of IN718(19) and Ti-6Al-4V.(20) Where cold work values were less than 5%, no relaxation of residual stresses occurred. The implication from these results is that cold work from shot peening, even at less than 100% coverage, is sufficient to induce significant residual stress relaxation in surface and near surface layers at modest temperatures. Where such reduction cannot be tolerated, surface enhancement techniques such as low plasticity burnishing and laser shock [(20)] which induce low cold work should be considered, or shot peening coverage controlled to provide adequate compression with minimum or controlled levels of cold working.

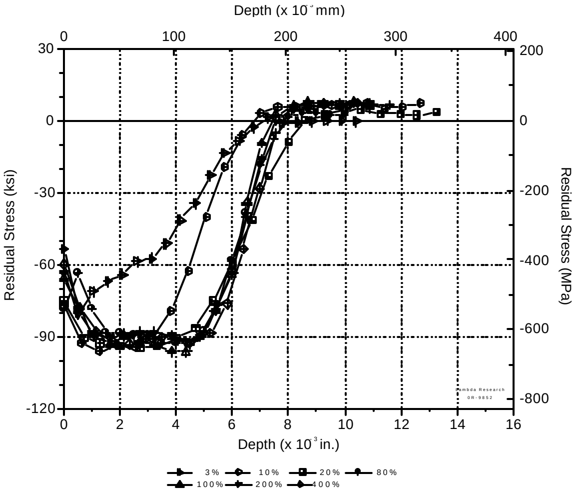

Figure 4. Residual stress-depth distributions after thermal exposure (475F/24 hr.)

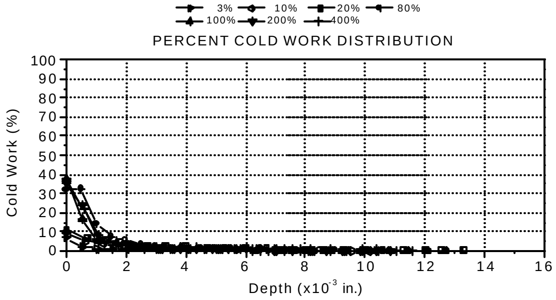

Figure 5. Cold work-depth distributions after thermal exposure (475F/24 hr.)

Fatigue Performance

Results of limited initial fatigue testing are presented in Figure 6, below. Significant surface and near surface compressive residual stresses were associated with the low stress ground condition. Hence, fatigue life for this condition was intermediate between lives for peened specimens and the electro-polished specimen, which had no residual stresses. Optical fractography revealed that subsurface fatigue origins occurred in all peened specimens and in the low stress ground specimen. No crack initiation sites in peened specimens were associated with undimpled surface areas irrespective of coverage. Therefore, the undimpled surface areas appear to be in compression. These results indicate the beneficial effect of peening relative to unpeened conditions. The results suggest further that, for R > 0 loading, the full benefit from peening can be realized at less than 100% coverage, although the limited number of initial tests did not permit assessment of an optimum coverage level, if any. This finding is in contrast to those of other investigators who have reported that fatigue life decreases dramatically with coverage less than 100%.[(8,9)]

Full S-N curves for a range of coverage were prepared to test the unexpected finding of uniform fatigue strength, independent of coverage. Because the residual stress depth and magnitude was found to be comparable for any coverage greater than 20%, samples were prepared with 20%, 100% and 300% coverage. The fatigue results, presented in Figure 7, indicate no loss of fatigue life or strength for coverage as low as 20%. The fatigue performances for 20% and 100% coverage are essentially equal, given the experimental uncertainty for the limited number of samples tested. Coverage of 300% produced consistently shorter lives and a slightly lower endurance limit than either 100% or 20% coverage.

When fatigue testing of shot peened surfaces is conducted in fully reversed loading, (R = –1.0), the compressive half-cycle superimposes a compressive applied stress on the already highly compressive shot peened surface. The compressive surface then yields in the first few cycles of testing resulting in rapid relaxation of the compressive surface layer. Surface residual stress measurement during fatigue testing reveals that even at alternating stress levels below the residual stress-free material endurance limit, the surface compressive stress can be reduced to 70% of the original level in the first half-cycle.(7) Residual stress measurements on failed samples in the current work showed no significant change in surface compression after 130 and 220 x 10^3 cycles at R = 0.1 and S_{max} of 1240 MPa (180 ksi) for either the 100% or 20% coverage samples, respectively.

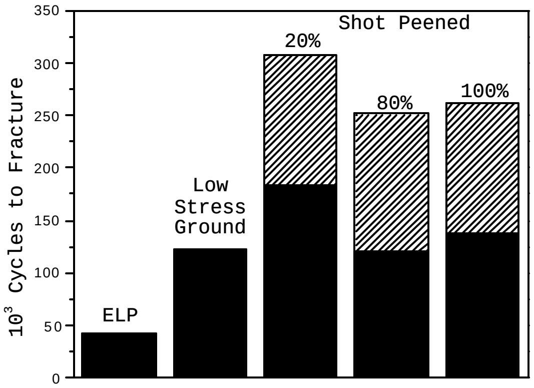

Figure 6. Bending fatigue lives at 1240 MPa (180 ksi), R= 0.1, for electropolished (ELP), low stress ground (LSG) and shot peened 4340 steel peened to the coverage indicated.

The apparent conflict between the lack of dependence of fatigue performance on shot peening coverage reported herein and work previously published is attributed to the stress ratio used in fatigue performance evaluation. Most of the prior studies of the effect of coverage on fatigue have employed fully reversed bending (R = -1) fatigue tests. It is well known that fully reversed bending of the highly compressive shot peened surface can drive the surface beyond yield in compression, causing rapid loss of compression in the initial cycles of the test.(19) The compressive overload relaxation process has been accurately modeled(22) and verified experimentally.(7,22) The benefits of shot peening are then reduced or lost entirely early in the test, depending upon the stress amplitude. The observed fatigue improvement with increased coverage may be due to increasing yield strength with work hardening of the surface with higher coverage. Confirmation of this hypothesis was beyond the scope of the present study, and will be addressed in the future. In tension-tension fatigue testing (R > 0), compressive overload is avoided, and the compressive residual stress survives without significant loss for the duration of the test at alternating stress levels appropriate for high-cycle fatigue failure.

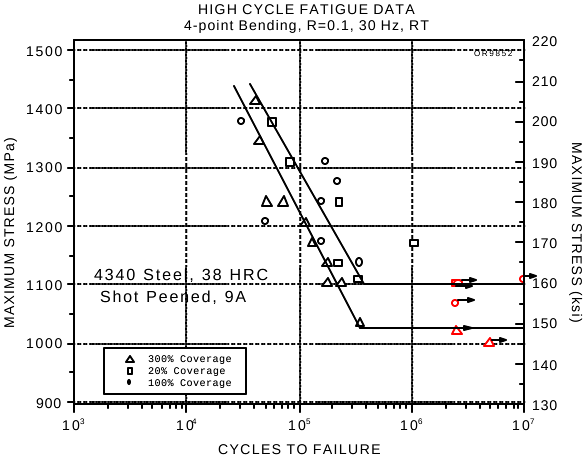

Figure 7. High-cycle fatigue results for shot peened 4340 steel, 38 HRC, at 20%, 100% and 300% coverage.

Summary

Results from this investigation have clearly demonstrated that complete coverage is not required to produce full benefits of shot peening in 4340 steel, 38 HRC, peened to 0.22 mmA (0.009 in.A) intensity when fatigue tested in tension-tension loading (R = 0.1). Indeed, a coverage level of as little as 20% (0.2T) provided fatigue performance equivalent to full coverage under conditions employed in this study. The principal objective of this work, however, has not been to establish an optimum coverage level although, by extension, such could be established for a given loading spectrum. Rather, it has been to show that full coverage is not required to achieve peening benefits. In a practical sense, this affords potential for significant improvements in current shot peening practice(23) in applications where compressive overload will not occur. Many practical applications of shot peening, from automotive leaf springs to compressor and turbine blades and disks, involve service loading at positive R-ratios. Reductions in peening processing times appear to be possible with obvious attendant economic benefit. Shot peening may be performed to reduced coverage with larger shot than is practical when at least 100% coverage is required, providing deeper compression and reduced cold work without loss of fatigue performance. Reduced cold work shot peening should provide improved thermal stability of the compressive layer.

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