

THE EFFECT OF SHOT PEENING COVERAGE ON RESIDUAL STRESS, COLD WORK AND FATIGUE IN A NICKEL-BASE SUPERALLOY

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ABSTRACT

The goal of this work was to determine effects of shot peening (SP) coverage on the compressive residual stress magnitude, depth, and relaxation of residual stresses due to thermal exposure, as well as fatigue strength of IN718, a nickel-base superalloy. The residual stress-depth profiles (both depth of compression and magnitude) for coupons shot peened to different coverage levels of 82% (0.2T where T = time to achieve full area coverage) to 400% (4T) show a slight trend of increased depth of compression with increase in coverage. Though having similar residual stress distributions, the coupons exhibited markedly different cold work distributions. While 82% (0.2T) coverage resulted in less than five percent cold work, increasing coverage to 400% (4T) resulted in cold work as high as thirty-five percent. The heavily cold worked surfaces of the higher coverage coupons exhibited significant relaxation of surface residual stresses, accompanied by corresponding reduction of cold work upon thermal exposure at 525°C for 10 hours. In contrast, the low cold work associated with lower SP coverage resulted in little relaxation of residual stresses under the same conditions. These observations were consistent with findings in other alloy systems. High cycle fatigue (HCF) performance at 525°C showed little dependence on peening coverage. Even with deeper compression achieved through low plasticity burnishing (LPB), the 525C fatigue performance of IN718 was only marginally improved. There may be other controlling elevated temperature fatigue mechanisms, such as oxidation, operating here that do not depend on residual stresses. HCF behavior at room temperature for the LPB treatment was significantly better than for SP treatment.

Introduction

SP coverage of at least 100% is thought to be necessary to achieve uniform surface compression and hence improved fatigue performance in metals. An earlier paper by the authors¹ had shown that, in SAE 4340 steel, coverage of as little as 70% (0.2T where T = time to achieve full area coverage) provided fatigue performance equivalent to full coverage. In a practical sense, this affords potential for significant improvements in current SP practice² via substantially reduced peening process cycle times in applications where compressive overloading will not occur in service. Also, reduced cold work that accrues to lower coverage SP should provide improved thermal stability of the compressive layer, and hence, improved elevated temperature fatigue performance. In

an attempt to understand the effects of thermal exposure and stress cycles, a study was undertaken in IN718 to evaluate the effect of thermal stability of compressive residual stresses from SP and the effects of SP coverage on the fatigue behavior at 525°C. Room temperature HCF results from surface treated IN718 were also obtained. SP was compared with LPB treatment.

Effect of Shot Peening Coverage on Residual Stress and Cold Work Distribution

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 conditioned cut wire shot (CCW14) 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 SP 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 SP standards.^{3,4,5,6} In this study, 100% area coverage was achieved in 7.0 minutes (intermittent peening on the turn table) while 4.0 minutes was required for saturation of the Almen strip under the same peening conditions. An alternative method of computing coverage from Abyaneh and Kirk⁷ was also used. The relative coverage values are listed below:

Duration of peening, minutes	0.67	1.33	2.83	3.33	4.33	5.5	7	14	28
Optical Coverage, %	61 (0.1T)	82 (0.2T)	85 (0.4T)	98 (0.48T)	99 (0.6T)	99 (0.8T)	100 (1T)	200 (2T)	400 (4T)
Coverage per Abyaneh and Kirk ⁷	52.6	79.3	96.4	98 (1X)	99.3	99.8	99.97 (2X)	100	100

Subsurface residual stress distributions were measured using conventional $\text{Sin}^2\psi$ methods with correction for stress relaxation due to layer removal and x-ray beam penetration into the stress gradient.⁸ The percent cold work, defined as the amount of

true plastic strain producing the observed diffraction peak broadening, was measured in conjunction with the macroscopic residual stress measurement.⁹ Figure 1 shows the residual stress and percent cold work distributions as a function of depth for various SP coverages. All the coupons showed surface compression in the range of -1035 to -1170 MPa (-150 to -170 ksi), and greater SP coverage generally produced higher surface compressive residual stresses. The depth of compression varied between 0.18 to 0.23 mm (0.007 to 0.009 in.) with no specific trend. While cold work less than 5% was recorded for 61% (0.1T) and 82% (0.2T) coverage conditions, the cold work progressively increased to over 30% as the coverage conditions increased to 85% (0.4T), 99% (0.6T), T, 2T and 4T. The effects of thermal exposure at 525°C for 10 hours on residual stress distribution and % cold work were examined, and the results are reported in Figure 2. The surface residual compression progressively relaxed with increased SP coverage conditions (increasing cold work). For example, for 61% (0.1T) coverage the surface compression relaxed from about -1035 MPa (-150 ksi) to about -880 MPa (-128 ksi), while for 4T coverage much greater relaxation from about -1138 MPa (-165 ksi) to about -345 MPa (-50 ksi) occurred. There was also a corresponding reduction in cold work. Even for 1T coverage, surface compression as seen in Figures 1 and 2 relaxed from about -1100 MPa (-160 ksi) to -620 MPa (-90 ksi). Thus it is obvious that there is very little to be gained from excess coverage, and in fact, SP coverage in excess of 85% (0.4T) can indeed be harmful if the part is likely to get thermal exposure. The effects of thermal exposure at 525 and 600°C on the compressive residual stress and percent cold work in LPB treated IN718 are shown in Figure 3. The SP coupon (Shot used: CCW14; Intensity: 0.2 mmA; Coverage: 4T) showed compression to a depth of < 0.2 mm (0.010 in.) associated with heavy cold work of 57%, while LPB is seen to produce compression to depths > 1 mm (0.040 in.) and very little (< 5%) cold work. Also, the near-surface compression in the SP material was nearly completely relaxed when exposed to 525 and 600 °C while the LPB treated coupons retained nearly all of the compression.

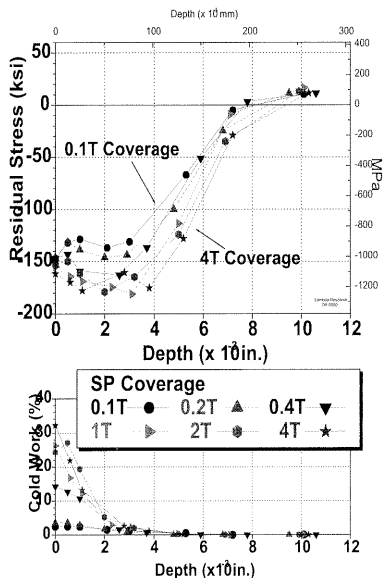


Figure 1 - Residual Stress and % Cold work distribution in SP and LPB treated IN718 coupons, showing the effects of different coverage.

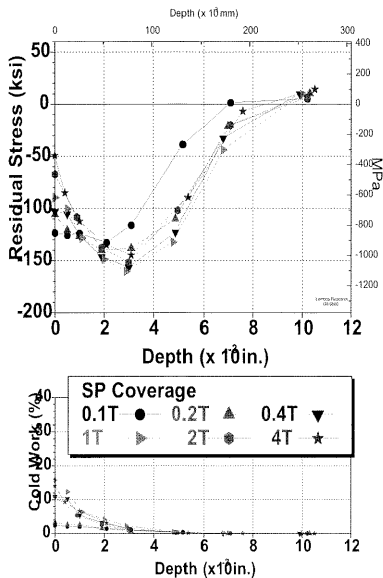


Figure 2 - Residual Stress and % Cold work distribution in SP and LPB treated IN718 coupons from Figure 4, after thermal relaxation treatment.

Effect of Shot Peening Coverage on Elevated Temperature HCF Behavior

Figure 4 shows the S-N data for HCF tests run at 525°C (in 4-point bending at stress ratio, R, of 0.1 and 30 Hz frequency) for the baseline condition (electropolished surface), in comparison with LPB treated surface and various SP coverage conditions. In the absence of foreign object damage (FOD), other than some subtle differences in the elevated temperature HCF behavior between surface treatments, all the data in Figure 4 may be considered to fall into one group with some small scatter. Fractographic analyses (Figures 5a to 5c) indicate that the subsurface residual stresses from the different treatment processes are substantially retained, even after fatigue cycling at 525°C. For example, multiple crack initiation from the specimen surface occurred in the electropolished specimen, while subsurface crack initiation occurred in SP and LPB treated specimens. Also, the subsurface initiation sites corresponded roughly to the depth of compression. Thus, in the absence of damage, there is no substantial difference in the HCF performance. However, prior surface damage (FOD, fretting, pitting, etc.) could seriously affect the HCF performance as shown for room temperature in the next section.

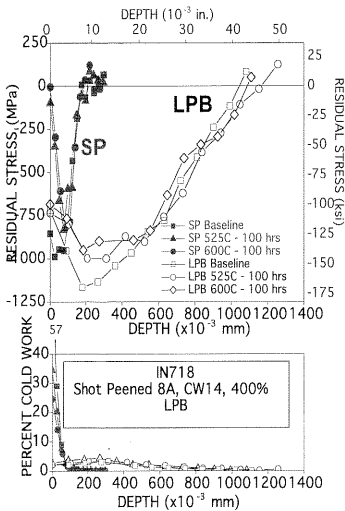


Figure 3 – Residual Stress and % Cold work distribution in SP and LPB treated IN718 coupons, before and after thermal relaxation treatment.

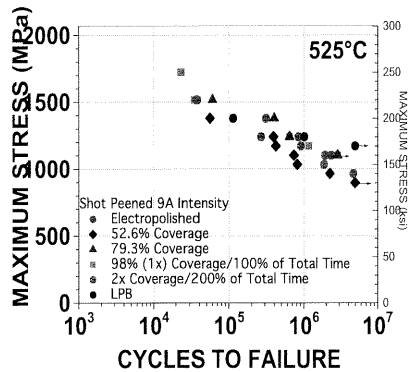
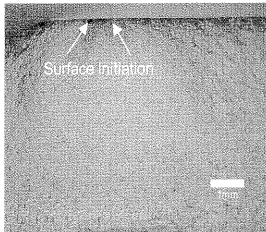
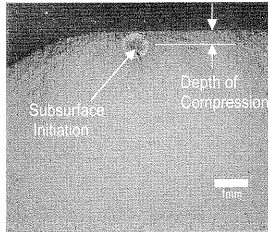


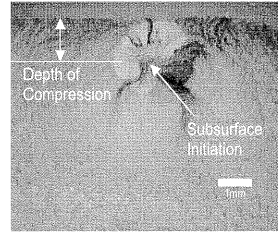
Figure 4 – Elevated temperature HCF results for smooth bar IN718 specimens with different SP coverage.



(a) $S_{max} = 180$ ksi, $N_f = 266,182$ cycles



(b) $S_{max} = 170$ ksi, $N_f = 1,164,635$ cycles



(c) $S_{max} = 180$ ksi, $N_f = 1,011,784$ cycles

Figure 5 – Fractographs showing the crack initiation (arrows) mechanisms for (a) electropolished, (b) 1X SP and (c) LPB.

Room Temperature HCF behavior

Figure 6 shows room temperature HCF data for surface treated IN718 (tests run in 4-point bending mode at a frequency of 30 Hz and a stress ratio, R of 0.1). The HCF behavior of LPB treated specimens is clearly superior to SP specimens after thermal exposures at 525 and 600°C. It is also important to note that the HCF performance shown here is well above the baseline untreated material with a reported room temperature fatigue strength (at 10⁷ cycles) of about 80 ksi (550 MPa).¹⁰ The benefits of compressive residual stresses are better seen with the introduction of simulated FOD. In Figure 7, the SP specimens showed a drop in fatigue strength at 10⁷ cycles of 50%

from 690 MPa (100 ksi) to about 345 MPa (50 ksi). In contrast, the LPB treated specimens showed less than 15% drop in fatigue strength from about 900 MPa (130 ksi) to about 800 MPa (115 ksi). Even at this, the fatigue strength of LPB treated specimens with FOD is seen to be better than the SP specimens absent of FOD. Also, the fatigue strength at 525°C at about 1035 MPa (150 ksi) is much greater than the room temperature fatigue strength. This improved fatigue strength at elevated temperature is characteristic of Ni-base superalloys like IN718.⁸

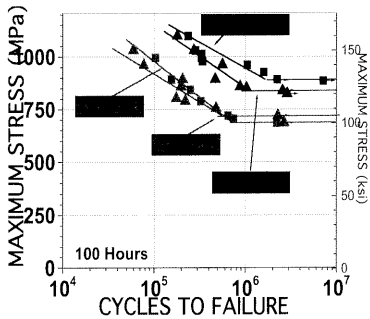


Figure 6 – Smooth bar HCF test results for surface treated IN718 at room temperature.

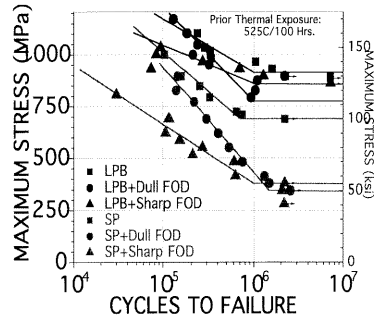


Figure 7 – Effect of simulated FOD on HCF results for surface treated IN718.

Summary

Compressive residual stress distributions from SP IN718 are minimally dependent on the coverage in the range of 0.1T - 4T. The cold work associated with the process was less than 5% at coverage levels of 0.1T, 0.2T, and progressively increased to over 30%. Increased cold work caused relaxation of surface residual stresses with exposure at 525 and 600°C. while subsurface residual stresses (up to 0.25 mm depth) were minimally affected by temperature. In comparison, LPB produced deeper compression (up to 1 mm.) with less than 5% cold work, and residual stresses were unaffected by thermal exposure. LPB treatment resulted in slightly better room temperature HCF performance than for SP while both were better than the baseline data available in literature for untreated material. The deeper compression associated with LPB resulted in superior HCF performance in the presence of simulated FOD, while the more shallow compression from SP resulted in a drastic reduction. Fractography indicated that all surface treated specimens failed by subsurface crack initiation at a depth nominally equal to the depth of compression.

References

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