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Effectiveness of Shot Peening in Suppressing Fatigue Cracking at Non-Metallic Inclusions in Udimet® 720

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Abstract

The fatigue lives of modern powder metallurgy disk alloys can be reduced by over an order of magnitude by surface cracking at inherent non-metallic inclusions. The objective of this work was to study the effectiveness of shot peening in suppressing LCF crack initiation and growth at surface nonmetallic inclusions. Inclusions were carefully introduced at elevated levels during powder metallurgy processing of the nickel-base disk superalloy Udimet® 720. Multiple strain-controlled fatigue tests were then performed on machined specimens at 427 and 650 °C in peened and unpeened conditions. Analyses were performed to compare the low cycle fatigue lives and failure initiation sites as a function of inclusion content, shot peening, and fatigue conditions. A large majority of the failures in as-machined specimens with introduced inclusions occurred at cracks initiating from inclusions intersecting the specimen surface. The inclusions could reduce fatigue life by up to 100X. Large inclusions had the greatest effect on life in tests at low strain ranges and high strain ratios. Shot peening can be used to improve life in these conditions by reducing the most severe effects of inclusions.

Introduction

The low cycle fatigue (LCF) lives and predominant failure modes of powder metallurgy (PM) nickel-base superalloy compressor and turbine disks can be influenced by material processing details including powder characteristics, consolidation, extrusion, forging, heat treating, and machining processing parameters. Among these variables, the effects of inherent non-metallic inclusions introduced during the PM production process have been shown to significantly degrade LCF life (refs. 1 to 3). It has been shown that for fixed fatigue test conditions, surface-initiated failures produce significantly lower fatigue lives than internally initiated failures (refs. 1and 2). Therefore, the effects on fatigue life of inclusions residing at or near the surface of a disk could be quite substantial. Modern nickel disk powder processing facilities have successfully reduced the levels of inclusion contamination to less than 1 part per million by weight. However, production quantities of full scale compressor and turbine disks have sufficient collective volume and surface area such that these inclusions may be present to an extent that they potentially limit life.

Shot peening is a surface enhancement process which produces beneficial compressive residual stresses on treated metallic surfaces. This process has been adopted nearly universally to improve the fatigue life of nickel-base disk superalloy components by reducing the propensity for cracks to initiate at machined surfaces. Shot peening could thereby be applied to possibly reduce the effects of surface inclusions on fatigue life of disk superalloys. However, the shot peening conditions which optimally minimize the effects of surface inclusions need to be studied and compared.

The objective of this work was to study the effectiveness of shot peening in suppressing LCF crack initiation and growth at surface nonmetallic inclusions in the powder metallurgy disk superalloy Udimet® 720. Since natural inclusions occur so infrequently on specimen surfaces, elevated levels of nonmetallic inclusions were introduced before consolidation in carefully controlled quantities and sizes into Udimet® 720 powder having very low inherent inclusion content. The seeded powder was then hot isostatically pressed, extruded, iso-forged into subscale disks, and heat-treated. The LCF lives of specimens machined from the seeded subscale disks were compared to those given shot peening in fatigue tests at 427 and 650 °C.

Materials and Procedures

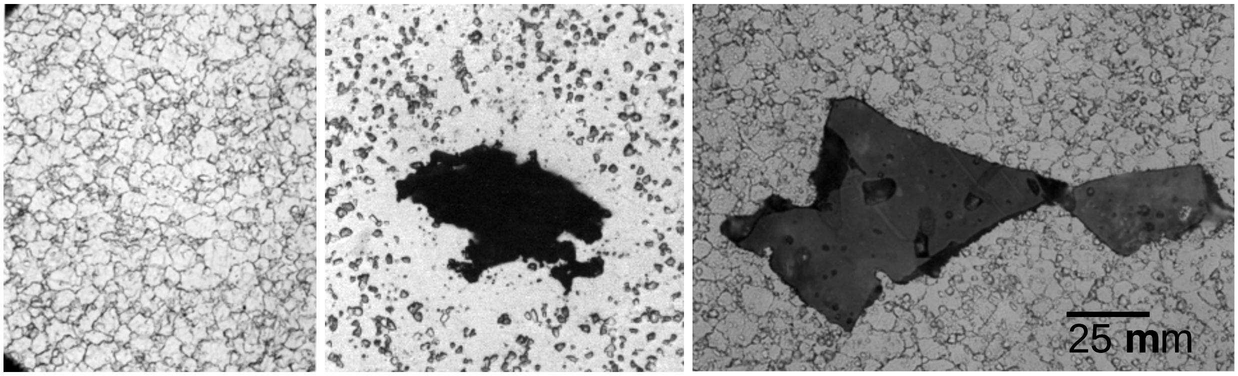
Material Processing

U720 powder was atomized in argon at Special Metals Corporation, Inc. This powder was produced and handled using state-of-the-art full-scale production practices to minimize powder contamination of any nature. The powder was then sieved through a –270 mesh screen and divided into three portions. Two portions were seeded with alumina particles, and one portion was consolidated in its unseeded condition.

The seeds were designed to behave in a similar manner to inclusions which are inherently present in conventionally processed powder. A sufficient quantity of seeds was added and fully blended in the superalloy powder to ensure that several inclusions would intersect the gage surface of each LCF test specimen (ref. 2). One portion of powder was seeded with smaller inclusions produced by crushing pre-baked Ram 90 alumina crucible paste. A second portion of powder was seeded with relatively large inclusions made of crushed Alcoa T64 alumina, a common crucible type material. The third portion of powder remained in its natural or unseeded condition to provide a baseline for comparison. Table I contains the details of the three powder portions.

TABLE I.—POWDER PORTION DETAILS

Powder Portion	Characteristics	Properties		
		Equivalent Dia. [μm]	Median Proj. Area [μm^2]	Description
I	Small Seeds	54	2316	Pre-baked Ram 90 alumina crucible paste
II	Large Seeds	122	11774	Alcoa T-64 alumina crucible material
III	Unseeded			Baseline material



(a) (b) (c)

Figure 1.—Typical microstructure of the (a) unseeded, (b) 54μm seeded, and (c) 122μm seeded disk forgings.

Three separate stainless steel cans were filled with the three powder portions. The three portions of powder were subsequently hot isostatically pressurized, extruded, and forged into disks approximately 17.5 cm in diameter and 4 cm thick. The disks were heat treated in a gas-fired furnace at Wyman-Gordon Forgings, Inc., in mixed groups of four, arranged in a consistent square array on a superalloy tray. The sub-solvus solution heat treatment was performed at 1120 °C for three hours. The tray of disks was then quenched at 50 °C in agitated oil after a one minute delay. The disks were then given an aging heat treatment of 760 °C for eight hours, followed by 650 °C for 24 hours. The resulting sub-solvus microstructures of the unseeded and seeded disks were quite comparable, figure 1. The typical grain size was approximately 8 μm, equivalent to ASTM 11. Undissolved primary gamma prime (γ'), as well as dissolved and precipitated cooling and aging γ' precipitate contents and sizes were all comparable between the unseeded and seeded disks. The seeded inclusions were often broken up and then stretched by the extrusion and forging processes, respectively, producing elongated and flattened ellipsoid-like morphology having lengths up to twice the maximum lengths of the original inclusions (refs. 5 and 6).

Specimen blanks were extracted by electro-discharge machining from the unseeded and seeded disks. The specimen sizes were designed to influence the occurrence probabilities of the inclusions. For the unseeded material, smaller specimens were tested to minimize the probability of a natural inclusion intersecting the specimen surface. For the seeded material, larger specimens were used to give sufficient probability of several seeded inclusions intersecting the specimen surface. Blanks 1.42 cm diameter and 5.33 cm long were machined from the unseeded disks aligned circumferential to the pancake centerline. Blanks 1.98 cm diameter and 8.26 cm long were machined from the seeded disks generally aligned in the same manner. Sections of IN718 were inertia welded to each end of each blank. The resulting assemblies were then machined by low stress grinding into low cycle fatigue specimens with the desired gage section dimensions (table II).

TABLE II.—SPECIMEN GAGE SECTION DIMENSIONS.

	Length [cm]	Diameter [cm]	Surface Area [cm^2]	Volume [cm^3]
Unseeded	1.91	0.64	3.8	0.6
Seeded	3.18	1.0	10.13	2.57

Shot peening procedures including intensity and coverage calibrations, nozzle and specimen masking, and other quality control issues were performed to AMS2432 specifications. Metal Improvement Corp. performed the shot peening using conditioned cut stainless steel wire with 360 μm (14 mil) mean diameter (CCW14). Specimens were rotated in a fixture while a translating nozzle maintained at a constant angle applied the shot at constant pressure and flow rate, using a computer controlled automated system. Residual stress and x-ray peak width were measured as functions of depth on screening

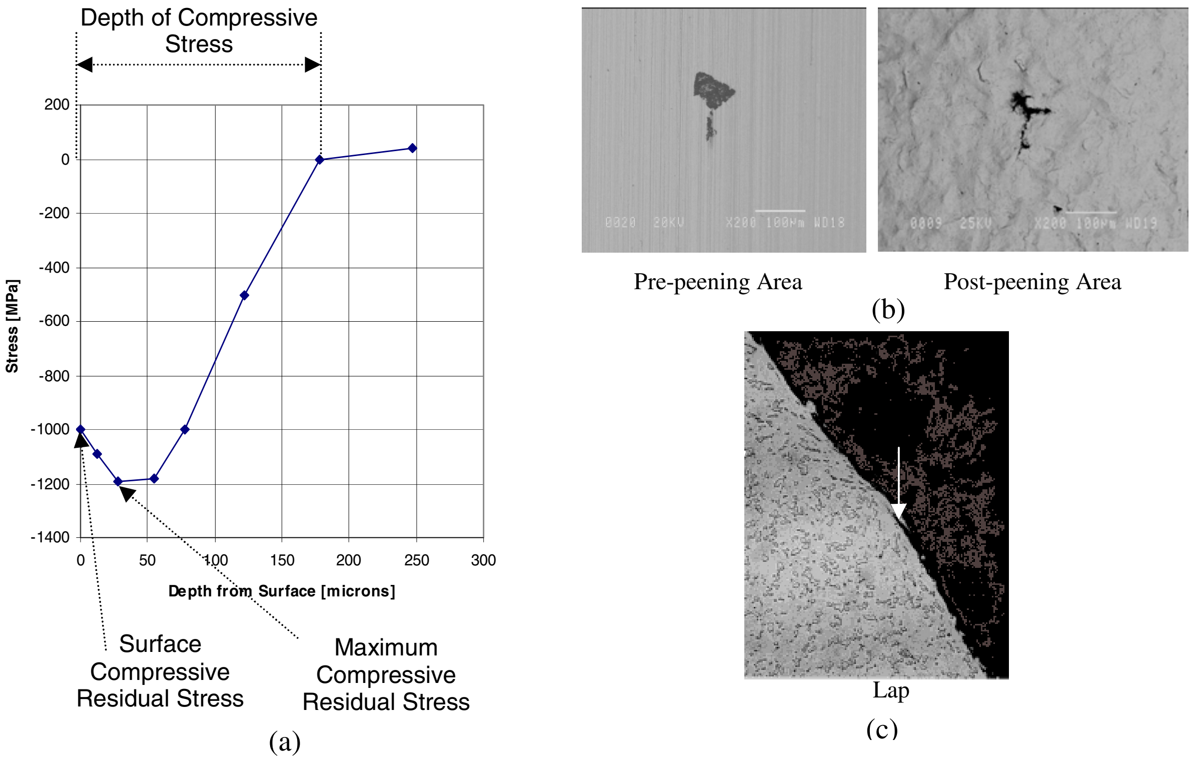


Figure 2.—(a) Representative plot residual stress profile with definitions of measured parameters, (b) inclusion intersecting the specimen surface before and after shot peening, (c) transverse metallographic section showing a lap due to shot peening

specimens by Lambda Research Incorporated (ref. 4). Metallographic sections were prepared transverse to shot peened surfaces for evaluations of the number of laps per linear surface width. For the purposes of this paper a lap is defined as any location where material was folded over itself on the surface. The inclusions intersecting several specimen surfaces were mapped and evaluated before and after shot peening, to determine the degree of surface material covering inclusions. Figure 2 shows representative plots and images of the parameters monitored for this study.

Mechanical Testing.—Fatigue tests were performed at 427 and 650 °C in closed-loop servo-hydraulic testing machines using induction heating and axial extensometers. The initial screening tests to select shot peening conditions were performed on the two seeded materials (large gage LCF specimens) by LCF testing at 650 °C, with a total strain range ($\Delta\varepsilon_t$) of 0.8 percent, and a strain ratio (R) of zero. Subsequent tests were performed at 427 and 650 °C using several total strain ranges and strain ratios of –1, 0, and 0.5. Each fatigue test was performed in two stages to reduce total testing time. For the first 24 hours, the test was conducted in strain control using a triangular waveform to produce a constant total strain range at a frequency of 0.33 hertz. After cycling for 24 hours, tests were continued to failure in load control using a triangular waveform to the stabilized maximum and minimum loads and stresses at a frequency of 5 hertz. All tests were continued to failure, and fractographic evaluations were performed on all specimens to determine the crack initiation sites.

Results and Discussion

Screening Tests of Shot Peening Conditions

Screening tests of shot peening conditions were performed to ascertain optimal shot peening conditions for seeded material. Screening tests were performed at extremes of 4 Almen (A) and 8A intensities, and coverages of 200 and 800 percent, as well as several intermediate coverages at 6A (table III).

TABLE III.—SHOT PEENING CONDITION SCREENING TEST MATRIX

Intensity	Coverage				
	200%	400%	500%	600%	800%
4A	X				X
6A		X	X	X	
8A	X				X

After shot peening, and prior to mechanical testing, measurements were made of the surface and maximum compressive residual stresses, depth of compression, peak width, laps per linear surface length, and the ratio of exposed inclusion surface area after/before shot peening for each shot peening condition. Simple scatter plots of each of the measured responses are shown versus the peening variables in figure 3. Fairly constant maximum compressive residual stresses exceeding 1000 MPa were produced in all cases. The surface compressive residual stress and peak width varied more with shot peening conditions. Linear variations of compression depth and surface peak width appeared significant; however, the relationships with other responses appeared less clear. Laps per linear surface length showed strong variations with intensity and coverage, while the ratio of exposed inclusion surface area measured after/before shot peening displayed smaller variation to intensity and coverage.

After pre-test measurements were completed, fatigue lives were measured in screening tests at $T = 650$ °C/ $\Delta\varepsilon_t = 0.8$ percent/$R_\varepsilon = 0$. The results are shown versus intensity and coverage for each seeded material in figure 4. Unseeded, shot peened specimens were not evaluated for fatigue life in this study. Life did not vary strongly with intensity and coverage for specimens with 54 µm seeds, but varied appreciably for specimens with 122 µm seeds.

Fractographic evaluations of the LCF tested screening specimens were performed. All of the 54 and 122 µm seeded specimens without shot peening failed from cracks initiating at surface inclusions. Shot peening at all combinations of conditions successfully suppressed this failure mode for the 54 µm seeded material, such that cracks initiating from internal inclusions caused failure. This was consistent with the significantly improved LCF lives over unpeened specimens for this material. However, the surface inclusion cracking mode was not so easily suppressed for 122 µm seeded material. In most combinations of shot peening conditions, cracks still initiated from surface inclusions which caused failure as in untreated specimens.

Only the high intensity, low coverage combination of 8A/200 percent succeeded in suppressing this cracking mode, such that the failure initiated at internal inclusions. The internal initiations resulted in a significant improvement in fatigue life for this condition.

In order to clearly assess and compare the effects of the shot peening variables on the responses, multiple linear regression was performed on each of the responses, using forward and reverse stepwise selection of the variables intensity (*I*), coverage (*C*), and specimen diameter (*D*) where applicable. The variables (*V*) were first standardized using equation (1).

$$V' = \frac{(V - V_{mid})}{(V_{range}/2)} \quad (1)$$

A 95 percent probability of significance was required for inclusion of any variable. The resulting relationships are listed along with the number of data points (n), residual degrees of freedom (resDoF), residual root mean square error (RMSerror), and correlation coefficient adjusted ($R^2_{adj.}$) for the variables in table IV. The correlation coefficient ($R^2_{adj.}$) was used as a measure of the applicability of the regression, with $R^2_{adj.} = 0.25$ indicating 50 percent of the response variation is accounted for by the regression.

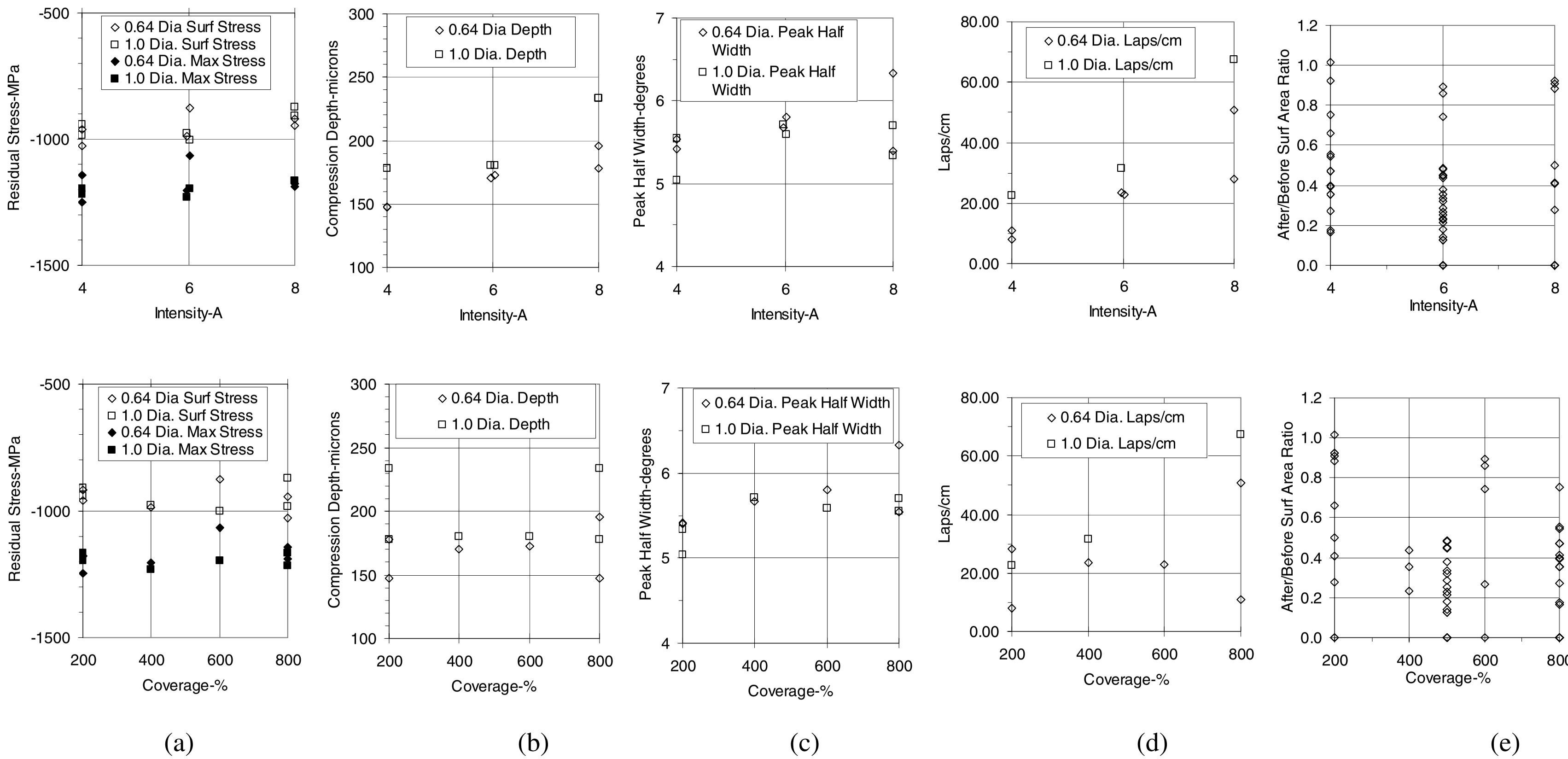


Figure 3.—Simple scatter plots of (a) surface and maximum residual stresses, (b) depth of compression, (c) peak half width, (d) laps per cm of surface length, and (e) inclusion surface area ratio after/before shot peening

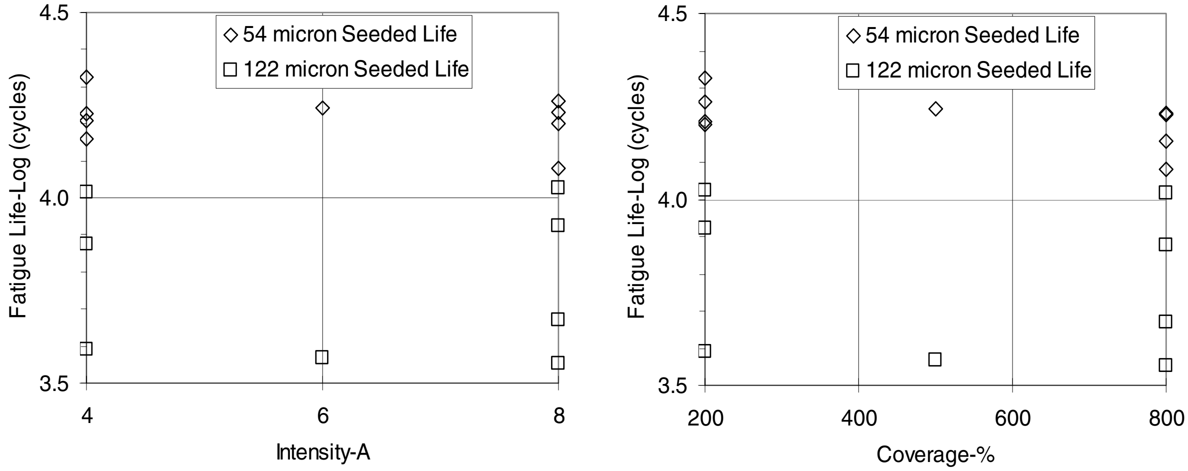


Figure 4.—Fatigue life versus intensity and coverage for seeded specimens, T = 650 °C, $\Delta\varepsilon_t = 0.8$ percent, $R_\varepsilon = 0$.

Analysis of the screening test data reveals the following trends:

1. The maximum compressive residual stress was very stable and did not vary significantly as a function of shot peening conditions.
2. Stress on the shot peened surface was less compressive with increasing intensity.
3. The surface x-ray peak width and corresponding cold work level increased with increasing coverage.
4. The depth of compressive stresses increased with increasing intensity and specimen diameter.
5. The laps/cm increased with increasingly intensity, coverage, and specimen diameter. While correspondingly the ratio of exposed inclusion area decreased.
6. Fatigue life of 54 µm seeded material was significantly improved for all combinations of shot peening conditions. Life moderately decreased with increasing coverage. Since all peening conditions resulted in internal initiations for specimens with 54 µm seeds, this was not unexpected.
7. A more complicated interactive relationship of intensity and coverage with fatigue life was observed for the 122 µm seeded material. Life increased with the combination of either high intensity and low coverage, or low intensity with high coverage.

TABLE IV.—REGRESSION RESULTS OF SCREENING TEST DATA

Variable	Relationship	n	res DoF	RMS error	$R^2_{adj.}$
Surface Stress [MPa]	$-950.1 + 33.75I'$	12	10	42	0.28
Depth of Compressive Stress [µm]	$182.6 + 23.9I' + 14.8D'$	12	9	11.9	0.81
Laps per cm of Surface Length [laps/cm]	$30.44 + 15.20I' + 6.6C' + 6.8D' + 6.0I'C'$	9	4	3.30	0.97
Inclusion Exposed Surface Area Ratio [After/Before]	$0.38 - 0.16I' - 0.17C'$	54	51	0.266	0.15
Surface Half Width	$5.59 + 0.23I' - 0.17C'$	12	10	0.25	0.36

The screening test results were used to select shot peening conditions. Intensities of 4-6A combined with 200 to 400 percent coverage gave attractive responses at the specimen surface: high magnitude compressive stresses, low cold work, and less lapping. However, the beneficial compressive residual stresses extended only 140 to 200 μm into the specimen depth. The associated LCF screening tests and fractography indicated these conditions were satisfactory for the 54 μm seeded surface-connected inclusions, however, 4-6A combined with 200 to 400 percent coverage did not suppress cracking at the larger 122 μm seeded inclusions, which extended greater distances into the specimen. Only the high intensity/low coverage condition of 8A/200 percent appeared to provide the necessary balance of high depth of compressive residual stresses combined with sufficient compressive stress, low cold work, and moderate lapping at the surface to suppress the surface inclusion cracking mode for the larger 122 μm seeded inclusions. Therefore, shot peening conditions of 8A intensity and 200 percent coverage were selected for further evaluations of effects on LCF strain-life response for seeded material.

Shot Peening Effects on Strain-Life Response at 8A Intensity and 200 Percent Coverage

Mechanical testing was performed to determine the effectiveness of the selected shot peening condition. Testing results are summarized in figure 5 with plots of LCF life versus total strain range. Plots in figure 5 compare unseeded, 54 μm seeded, and 122 μm seeded results in either unpeened or 8A/200 percent conditions at 427 and 650°C at strain ratios of -1, 0, and 0.5. Fractography was performed on all specimens to determine whether each failure initiated at a surface or internal failure origin, which is indicated by open or solid symbols, respectively.

For the unpeened specimens, the lives of seeded specimens were invariably lower than unseeded specimens. The 122 μm inclusions reduced life more than the 54 μm inclusions for fixed test conditions at 650°C. However, the two seed sizes produced similar reduced lives at 427°C. For a given strain ratio, the inclusions reduced lives on a percentage basis more at lower strain ranges than for high strain ranges. For a given strain range, unseeded and seeded specimen lives were lower at positive strain ratios. Inclusion effects on life were thereby maximized in tests at the lowest strain range of 0.6 percent and the most positive strain ratio of 0.5. In these conditions at 650 °C, small seeds reduced life by approximately 20X, while larger seeds dramatically reduced life by 100X. The large reductions in life were associated with failures initiated from inclusions extending in from the specimen surface, as shown in figure 6.

For the shot peened specimens, at strain ranges of 0.6 and 0.8 percent with strain ratios of –1 and 0, shot peening improved life at both 427 and 650 °C by between 2X and 9X. Shot peening successfully suppressed surface cracking at inclusions in these test conditions, with failures usually initiating at internal inclusions as seen in figures 7 and 8 for tests at 650 °C. The greatest improvements in lives of seeded materials were observed at these conditions. The failure mode changed from surface inclusion cracking for unpeened specimens to internal inclusion cracking for shot peened specimens. It is interesting to note that although life was extended by peening at these conditions, the observed lives of the peened, seeded specimens never attained the lives of the unpeened, unseeded specimens.

There are two primary factors which may explain why the internally initiated failures of shot peened, seeded specimens occurred at lower lives than that of the unpeened, unseeded specimens. First, the presence of many more inclusions throughout the gage volume of the seeded specimens allowed the fatigue damage to occur and compete at numerous inclusions. Cyclic damage was accelerated by the largest; most harmfully shaped and oriented inclusion, and therefore controlled life. This is supported by the trend that lives increased in the material order: 122 μm seeded, 54 μm seeded, followed by unseeded material. As expected, the corresponding sizes of inclusions initiating these failures usually increased with the reverse material order: unseeded, 54 μm seeded, followed by 122 μm seeded materials.

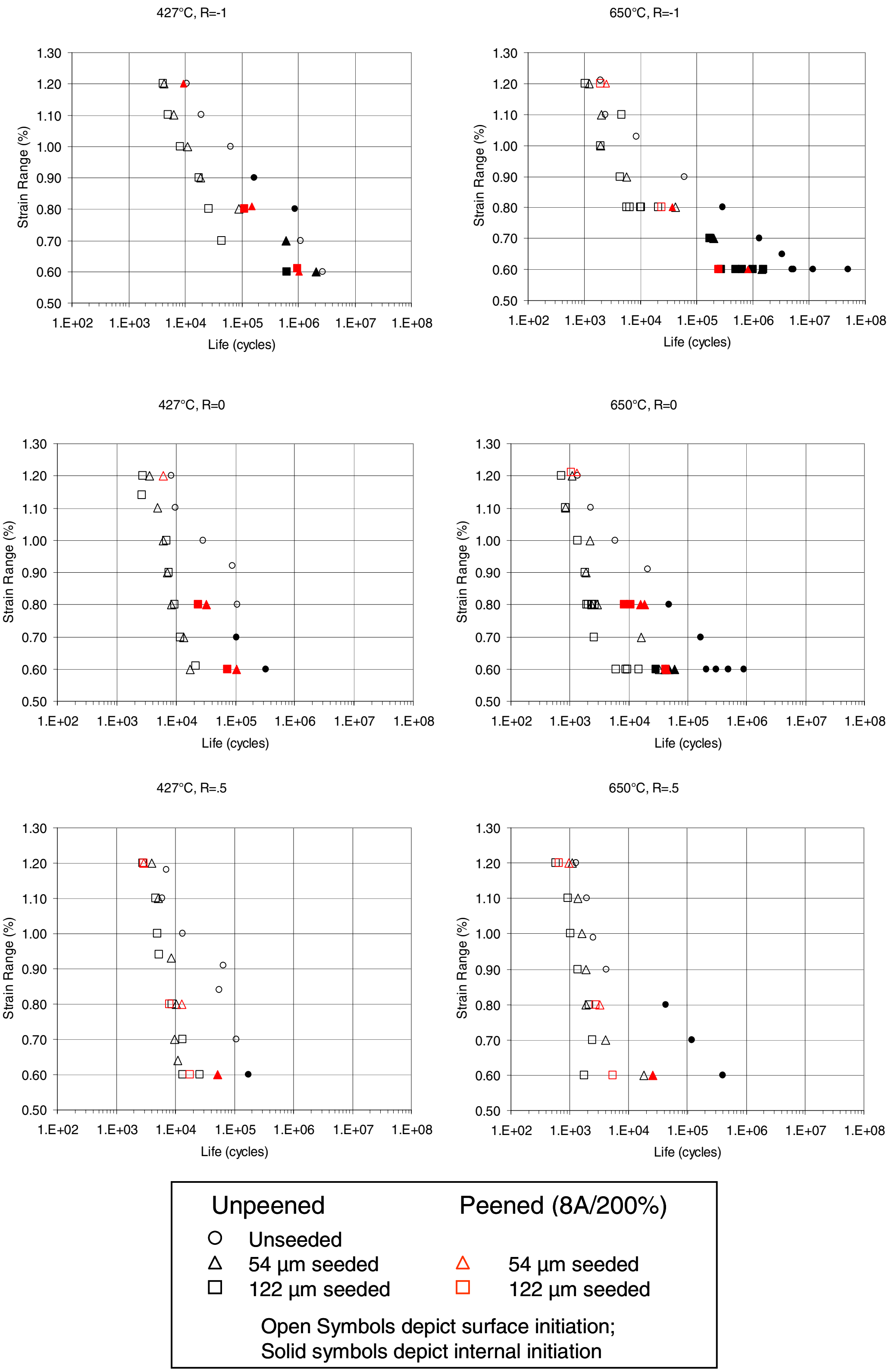
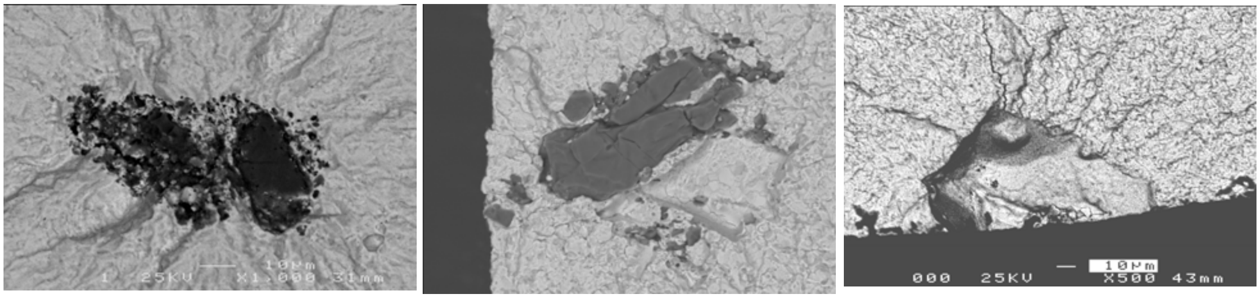


Figure 5.—Strain life response of unseeded, 54 µm seeded, and 122 µm seeded Udimet® 720.



(a) (b) (c)

Figure 6.—Representative fractography of unpeened specimens (a) unseeded, (b) 54 µm seeded, and (c) 122 µm seeded, T = 650 °C, $\Delta\varepsilon_t$ = 0.8 percent, R_ε = .5.

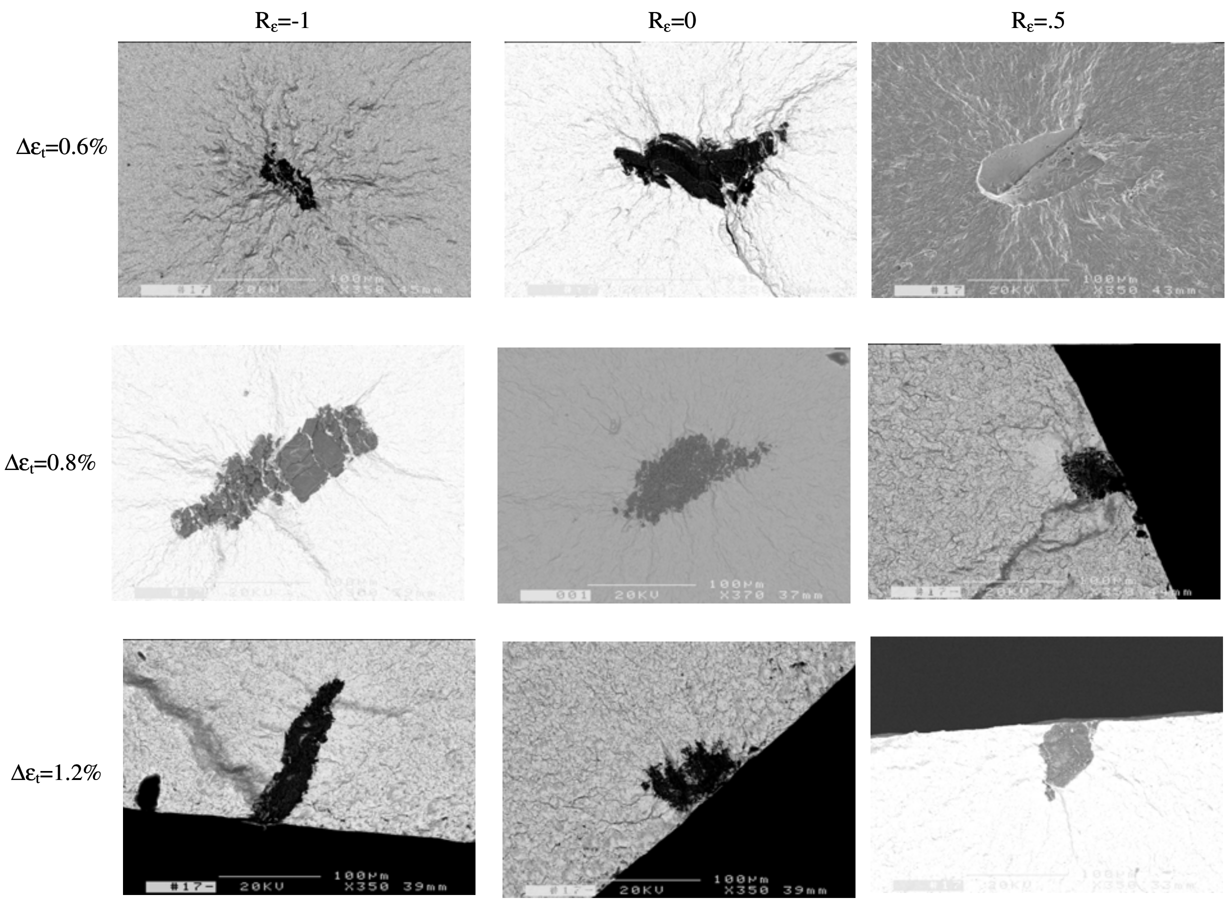


Figure 7.—Representative fractography of 8A/200 percent peened, 54 µm seeded specimens, T = 650 °C.

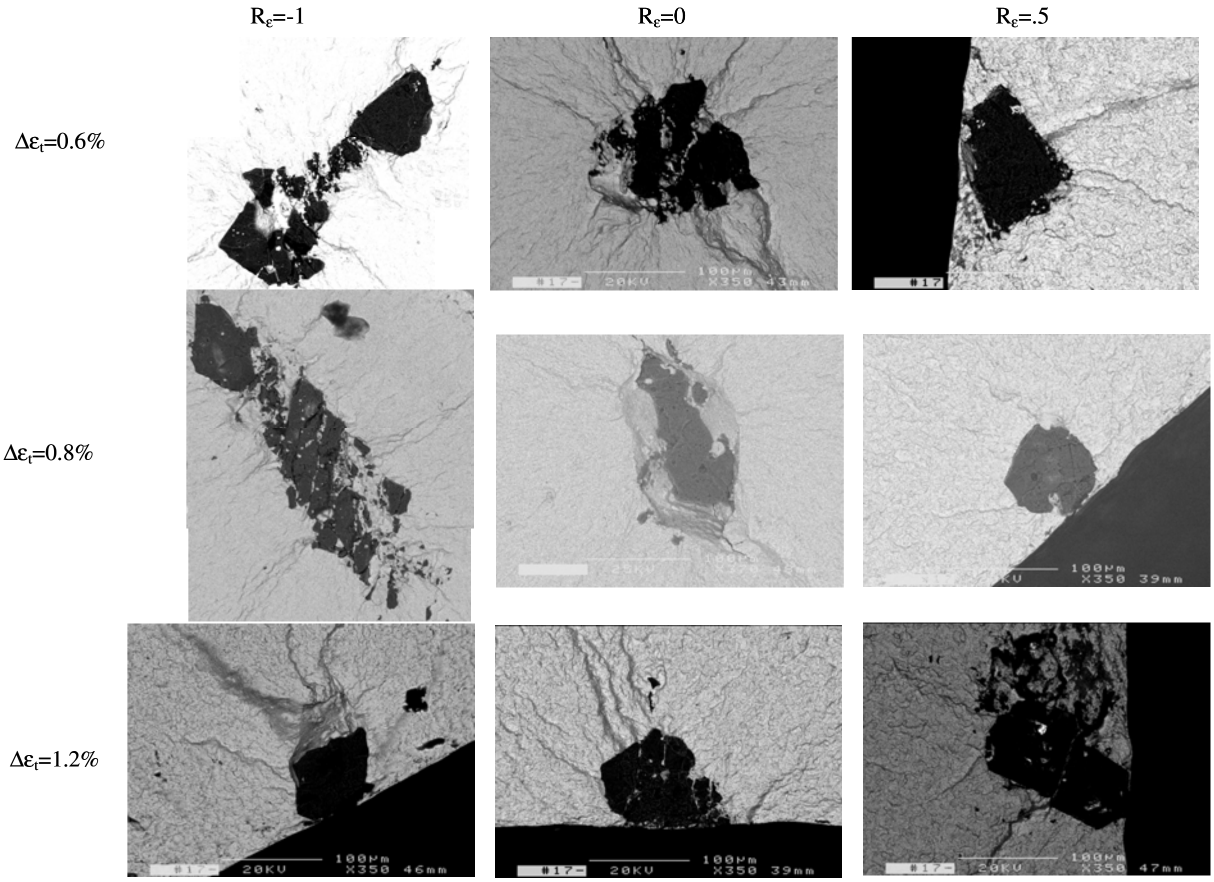


Figure 8.—Representative fractography of 8A/200 percent peened, 122 µm seeded specimens, T = 650 °C.

Second, tensile residual stresses are present in the interior of the specimens as a consequence of the compressive residual stresses near the surface. Longitudinal compressive residual stresses near the surface were found in the x-ray stress profiles to be balanced by internal longitudinal tensile elastic stresses, generated to maintain static equilibrium. This would result in a higher mean strain and stress at internal inclusions for shot peened specimens than for untreated specimens during fatigue cycling.

At a high strain ratio of $R_\varepsilon = 0.5$, surface cracks at inclusions often still caused failure regardless of surface peening. Surface cracking at 54 µm inclusions was suppressed at the lowest strain range of 0.6 percent, however, surface cracking at the larger 122 µm inclusions initiated failure despite peening. Surface cracking at both seed sizes caused failure at a strain range of 0.8 percent. A moderate improvement in life of 3X was observed. At a strain range of 1.2 percent, shot peening did not significantly improve life and could not suppress surface cracking at inclusions for any of the strain ratios. At a strain range of 0.8 and 1.2 percent, plastic strains of approximately 0.2 and 0.3 percent are generated on the first fatigue cycle, respectively. X-ray diffraction measurements of the surface stresses on several specimens after these tests indicated that the majority of the beneficial compressive residual stresses produced by shot peening were eliminated by these high initial plastic strains.

Many disk applications require low cycle fatigue lives of at least 15,000 to 30,000 cycles. During service, stabilized cyclic strain ranges at critical locations would not be expected to exceed 0.8 percent, in order for the disk to have sufficient life without considering inclusion effects. In such conditions, shot peening was effective in suppressing cracking at surface inclusions, for strain ratios of 0 to –1. Therefore, shot peening could be used to minimize the effects of inclusions intersecting the surface at critical disk locations in such cases, provided the strain ratio is not too high.

Remaining Issues

The results indicate shot peening can be optimized to reduce the effects of inclusions intersecting the surface of disk alloy specimen surfaces. However, additional issues must be addressed to implement such an approach for disk applications:

1. The processes of cyclic crack initiation and crack propagation at surface inclusions need to be separated through interrupted testing of additional specimens.
2. The effects of thermal exposure and cyclic overstrains on the compressive residual stresses must be understood (ref. 7).
3. Shot peening effects on life and surface inclusion cracking tendencies need to be evaluated for various disk machining processes.
4. The effects of realistic disk features, volumes, and stress states need to be evaluated.
5. While optimizing peening conditions to mitigate surface initiation from inclusions, care must be taken to ensure that the peening conditions do not adversely affect the LCF behavior of the base material by introducing a large amount of coldwork.

Summary of Results and Conclusions

The effectiveness of shot peening in suppressing LCF crack initiation and growth at surface nonmetallic inclusions was evaluated in the powder metallurgy disk superalloy Udimet® 720. Initial tests of untreated specimens indicated up to 100X reduction in fatigue lives due to failures initiating from surface inclusions. Shot peening conditions were then specifically screened and selected to suppress this failure mode. High intensity, low coverage conditions successfully suppressed surface inclusion cracking, and improved fatigue life in the screening tests. Subsequent LCF tests of shot peened, seeded material specimens indicated these improvements were possible at both 427 and 650°C, for strain ranges up to 0.8 percent and strain ratios of –1 and 0. The initial cyclic plastic strains generated at higher strain ranges and strain ratios apparently reduced the magnitude of shot peening’s compressive residual stresses sufficiently to eliminate these improvements.

It can be concluded from this work that:

1. Shot peening can be used to reduce the harmful effects of surface inclusions on disk fatigue life.
2. Shot peening is effective when beneficial compressive residual stresses are generated and maintained during cycling sufficient to suppress cracking at surface inclusions.
3. High plastic strains during initial cycling can act to reduce the magnitude and effectiveness of the compressive stresses in suppressing surface inclusion cracking.
4. The effects of thermal relaxation, overstrains, machining processes, and disk features need to be considered in order to utilize these life improvements in disk applications.

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13. ABSTRACT ***(Maximum 200 words)***
The fatigue lives of modern powder metallurgy disk alloys can be reduced by over an order of magnitude by surface cracking at inherent non-metallic inclusions. The objective of this work was to study the effectiveness of shot peening in suppressing LCF crack initiation and growth at surface nonmetallic inclusions. Inclusions were carefully introduced at elevated levels during powder metallurgy processing of the nickel-base disk superalloy Udimet® 720. Multiple strain-controlled fatigue tests were then performed on machined specimens at 427 and 650 °C in peened and unpeened conditions. Analyses were performed to compare the low cycle fatigue lives and failure initiation sites as a function of inclusion content, shot peening, and fatigue conditions. A large majority of the failures in as-machined specimens with introduced inclusions occurred at cracks initiating from inclusions intersecting the specimen surface. The inclusions could reduce fatigue life by up to 100X. Large inclusions had the greatest effect on life in tests at low strain ranges and high strain ratios. Shot peening can be used to improve life in these conditions by reducing the most severe effects of inclusions.

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