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Initial Assessment of the Effects of Nonmetallic Inclusions on Fatigue Life of Powder-Metallurgy-Processed Udimet® 720

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Abstract

The fatigue lives of modern powder metallurgy (PM) disk alloys are influenced by variabilities in alloy microstructure and mechanical properties. These properties can vary due to the different steps of materials/component processing and machining. One of these variables, the presence of nonmetallic inclusions, has been shown to significantly degrade low-cycle fatigue (LCF) life (refs. 5 to 8). Nonmetallic inclusions are inherent defects in powder alloys that are a by-product of powder-processing techniques. Contamination of the powder can occur in the melt, during powder atomization, or during any of the various handling processes through consolidation. In modern nickel disk powder processing facilities, the levels of inclusion contamination have been reduced to less than 1 part per million by weight. Despite the efforts of manufacturers to ensure the cleanliness of their powder production processes, the presence of inclusions remains a source of great concern for the designer. The objective of this study was to investigate the effects on fatigue life of these inclusions. Since natural inclusions occur so infrequently, elevated levels of inclusions were carefully introduced in a nickel-based disk superalloy, Udimet® 720 (registered trademark of Special Metals Corporation), produced using PM processing. Multiple strain-controlled fatigue tests were then performed on this material at 650 °C. Analyses were performed to compare the LCF lives and failure initiation sites as functions of inclusion content and fatigue conditions.

A large majority of the failures in specimens with introduced inclusions occurred at cracks initiating from inclusions at the specimen surface. The inclusions could reduce fatigue life by up to 100×. These effects were found to be dependent on strain range and strain ratio. Tests at lower strain ranges and higher strain ratios produced larger effects of inclusions on life.

Introduction

When performing fatigue specimen testing to develop fatigue life prediction models, it is very important to understand and account for all possible failure modes. The low-cycle fatigue (LCF) lives and predominant failure modes of powder metallurgy nickel-based superalloy compressor and turbine disks can be influenced by material processing details including powder characteristics, consolidation, extrusion, forging, heat treating, and machining processing parameters (refs. 1 to 4). These effects on fatigue

behavior can vary as functions of service/testing conditions: temperatures, times, and imposed stresses/strains. Among these variables, the effects of inherent nonmetallic inclusions introduced during the powder metallurgy (PM) production process have been shown to significantly degrade LCF life (refs. 5 to 8). It has been shown that for fixed fatigue test conditions, surface-initiated failures produce significantly lower fatigue lives than internally initiated failures (ref. 1). Therefore, the effects on fatigue life of inclusions residing at or near the surface of a disk could be quite substantial. However, in modern nickel disk powder processing facilities, the levels of inclusion contamination have been reduced to less than 1 part per million by weight. It is therefore exceedingly difficult to assess the full effects of inclusions on life with a statistically significant manner due to very low probability of inclusions occurring in a typical specimen's gage volume of 0.5 to 1.5 cm^3 and gage surface area of 1 to 4 cm^2. Yet, large quantities of compressor and turbine disks each with volumes from 500 to 50 000 cm^3 and corresponding surface areas do have sufficient collective volume and surface area for these inclusions to be present in some disks and to potentially limit life.

The objective of this work was to study the effects of nonmetallic inclusions on the LCF life and failure modes of the PM disk alloy Udimet 720. Since natural inclusions occur so infrequently, elevated levels of nonmetallic inclusions were introduced before consolidation in carefully controlled quantities and sizes into powder having very low inherent inclusion content. This seeded powder was then hot isostatically pressed, extruded, forged into subscale disks, and heat-treated. Identical subscale disks were created with unseeded PM material following the same production process. The LCF lives of specimens machined from the seeded and unseeded subscale disks were compared in fatigue tests at 650 °C.

Materials and Procedures

Material Processing

U720 powder was atomized in argon at Special Metals Corporation. This powder was produced and handled using state-of-the-art full-scale production practices to minimize powder contamination of any nature (ref. 9). The powder was then passed through a 270-mesh screen. The powder was then 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 represent commonly occurring inclusions, which are present in conventionally processed powder. Using a probabilistic model simulating inclusions within the specimen gage volume as flattened spheroids, 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. One portion of powder was seeded with relatively large inclusions made of crushed Alcoa T64 alumina, a common crucible material. These seeds were first crushed and then screened to obtain the desired size. The desired size range was obtained by separating inclusions which could pass through a 140-mesh screen, but were held by a 170-mesh screen. This gave a tight estimated size range of –140/+170 mesh, or approximate diameter of 122 μm and median projected area of 11 774 μm^2. A second portion of powder was seeded with smaller inclusions produced by crushing prebaked Ram 90 alumina crucible paste. The desired size range of these seeds was selected by separating inclusions, which could pass through a 270-mesh screen for an approximate diameter of 54 μm and a median-projected area of 2316 μm^2. The third portion of powder remained in its natural or unseeded condition to provide a baseline for comparison.

Three separate stainless steel cans were filled with the three powder portions, with small samples extracted during filling of each can. The quantity, size, and chemistry of inclusions in each of the small samples of powder were then verified. Heavy metal liquid separation was used to separate the inclusions from each sample (ref. 10). The inclusions were then filtered and evaluated using a fully automated inclusion detection and analysis system integrated on a scanning electron microscope. Energy dispersive x-ray

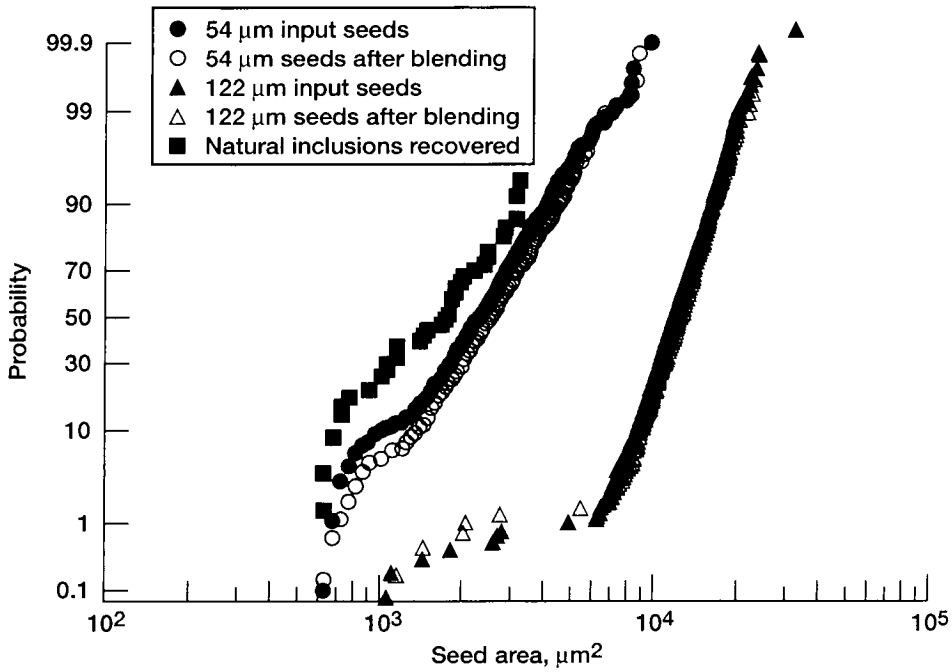

Figure 1.—Probability plot of seeded inclusion-size distribution before and after blending with the superalloy powder.

analyses were used to identify the alumina and other inherent inclusions. The sizes of seeds as measured by image analysis before and after blending into the powder compared very well (fig. 1). While it is very difficult to count all seeds separated from a sample, several trials were performed to ensure that at least 80 percent of the calculated number of introduced seeds had been recovered and measured from the seeded samples after blending in the powder. These results confirmed that a majority of the seeds were retained in the powder and did not break up during blending. The sizes of inclusions extracted from samples of the unseeded portion of powder are also shown for comparison. A very low number of inclusions were present in the unseeded powder, confirming the very good quality of modern powder production and handling practices. This corresponded to a seed mass density of less than 0.1 ppm in the unseeded powder.

The three portions of powder were subsequently handled, consolidated, forged, and heat-treated using conditions typically reported in the literature for Udimet 720 (refs. 4, 8, and 11). Each powder portion was poured into separate stainless steel containers of 19 cm in diameter and vacuum sealed. The sealed containers were hot isostatically pressed in argon. They were then extruded using a 6:1 extrusion ratio. After removal of representative metallographic sections from each extrusion, each billet was machined to cylindrical sections about 8.9 cm in diameter and 16.5-cm long. The sections were forged by Wyman-Gordon Forgings, Inc. to about 75 percent upset. These forged pancakes were then machined to disks about 17.5 cm in diameter and 4-cm thick.

The disks were heat-treated in a gas-fired furnace at Wyman-Gordon in mixed groups of four arranged in a consistent square array on a superalloy tray. The solution heat treatment was performed at about 1120 °C for 3 hr. The tray of disks was then transferred in about 1 min to a tank containing agitated oil held at a temperature of about 50 °C. A disk containing four imbedded thermocouples in firm contact with the metal was included in one of the heat-treat runs to determine the cooling rates during removal. The cooling rates averaged over 870 to 1120 °C were about 100 °C/min for the disk center and 150 °C/min for a disk corner location 0.3-cm deep from the edge and top surface. Quench cracks were not found in any of the disks. The disks were then given an aging heat treatment of about 760 °C/8 hr + 650 °C/24 hr.

Mechanical Testing

Specimen blanks were extracted by electrodischarge machining from unseeded and seeded disks. Specimen blanks were removed from various locations having cooling rates between the two extreme cooling rates indicated above from the thermocouple measurements. Blanks 1.42 cm in diameter and 5.33-cm long were machined from the unseeded disks aligned circumferential to the pancake centerline. Blanks 1.98 cm in 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, and the resulting assemblies were then machined into LCF specimens. The specimen sizes were designed to influence the occurrence probabilities of the inclusions (table I). For the unseeded material, smaller specimens were tested to reduce the probability of a natural inclusion causing surface fatigue-crack initiation. For the seeded material, larger specimens were used to increase the probability of fatigue-crack initiation from a surface seed inclusion.

Table I.—Specimen Dimensions

	Gage section properties			
	Length, cm	Diameter, cm	Surface area, cm^2	Volume, cm^3
Unseeded	1.91	.64	3.8	0.6
Seeded	3.18	1.02	10.13	2.57

Fatigue tests were performed at 650 °C in closed-loop servohydraulic testing machines using induction heating and axial extensometers. Each fatigue test was performed in two stages to reduce total testing time. First, the test was conducted in strain control conditions using a triangular waveform at a frequency of 0.33 Hz. After cycling for 24 hr, tests were continued to failure with load controlled using a triangular waveform to the same stabilized maximum and minimum loads previously achieved for each specimen at a frequency of 5 Hz. Past testing has shown that the change-in-control mode has negligible effects on fatigue life in these conditions (ref. 8). All tests were continued to failure, and fractographic evaluations were performed on all specimens to determine the crack initiation sites.

Results and Discussion

Metallographic Characterizations

Typical microstructures of unseeded and seeded disks were quite comparable (fig. 2). The typical grain size was about 8 μm, equivalent to ASTM 11. Undissolved "primary" γ' as well as dissolved and precipitated "cooling" and "aging" γ' precipitate contents and sizes were all comparable between the unseeded and seeded disks. No significant differences were detected in the superalloy microstructure between the unseeded and seeded disks, reflecting the common powder blend and common processing batch approach used for all disks.

Fatigue Test Results

Plots of fatigue life versus total strain range are compared for seeded and unseeded specimens tested at each strain ratio in figure 3. Lives of seeded specimens were invariably lower than unseeded

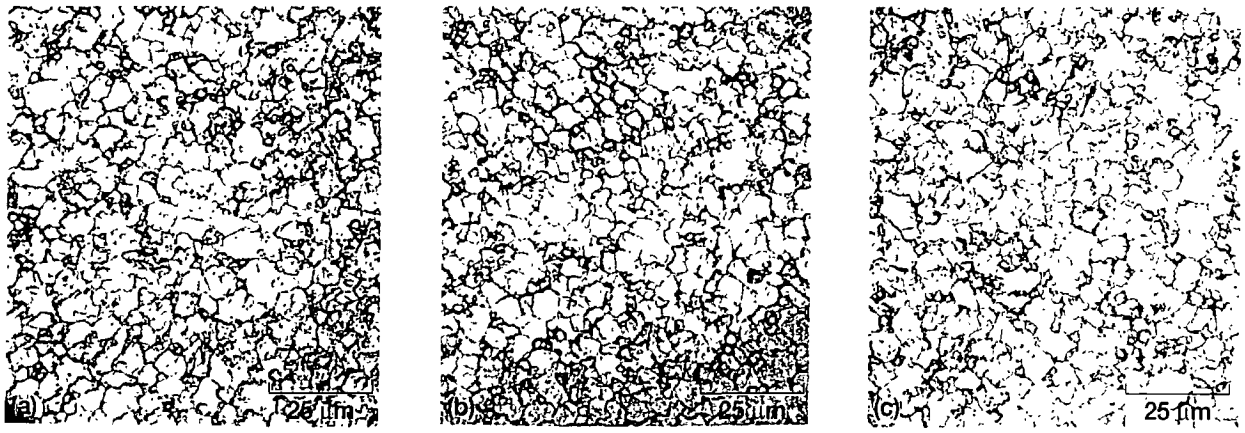

Figure 2.—Typical microstructures of disks. (a) Unseeded. (b) With 54 µm seeded inclusions. (c) With 122 µm seeded inclusions.

specimens. The large 122 µm inclusions reduced life more than the smaller 54 µm inclusions for fixed test conditions. For a given strain ratio, the inclusions reduced lives on a percentage basis more at lower strain ranges and longer lives 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 most positive strain ratio of 0.5. In these conditions, small seeds reduced life by about 20×, while larger seeds dramatically reduced life by 100×.

A nonlinear regression model was generated using the test control parameters of strain range ($\Delta\varepsilon$ in mm/mm) and strain ratio ($R_\varepsilon = \varepsilon_{min}/\varepsilon_{max}$), along with mean log inclusion areas (A in cm^2) and inclusion area densities (D in inclusions/cm^2) measured from metallographically prepared chord slices of unseeded and seeded disks. The intent of this model was to statistically derive a simple relationship among the input variables that could clearly describe the effects, rather than to fit an existing fatigue life model. Both forward and reverse stepwise regression was performed using a 95 percent probability of significance necessary to enter. Residual analyses were performed to ensure predominantly random residual error remained after regression. Analyses indicated interactions between the effects of inclusion size and strain range were significant, reflecting that increasing inclusion size had a larger effect on life at low strain ranges. Interactions between the effects of inclusion density and strain range were significant as well, reflecting that increasing inclusion density had a larger effect on life at low strain ranges. Interactions between the effects of strain ratio and strain range were also significant, reflecting that increasing strain ratio had a larger effect on life at low strain ranges. These effects are evident when comparing life versus strain ratio in figure 4. The resulting relationship obtained was

$$\text{Log(life)} = 4.275730 - 6.35604 \times 10^{-5}(1/\Delta\varepsilon^2) + 0.270572R_\varepsilon - 0.097913D + 0.350581 \log(A) - 5.73917 \times 10^{-5}(1/\Delta\varepsilon^2)R - 4.2260 \times 10^{-5}(1/\Delta\varepsilon^2)D - 3.81677 \times 10^{-5}(1/\Delta\varepsilon^2)\log(A)$$

This relationship had an adjusted correlation coefficient R^2_{adj} of 0.9524 and root mean square error of 0.225 in units of log(life). As shown in figure 5, a majority of the lives were estimated within 2×, which was considered satisfactory. Life lines generated using this regression model are included with the experimental results in figure 3.

Fatigue Failure Sites

Typical crack initiation sites of the unseeded specimens are shown in figure 6. Unseeded specimens failed predominantly from cracks initiated at small granulated "Type 2" aluminum + silicon oxide-rich inclusions, larger single particle "Type 1" titanium + iron oxide-rich inclusions, and micropores. Initiation sites tended to be located near or at the surface in tests at high strain ranges above 0.8 percent, and

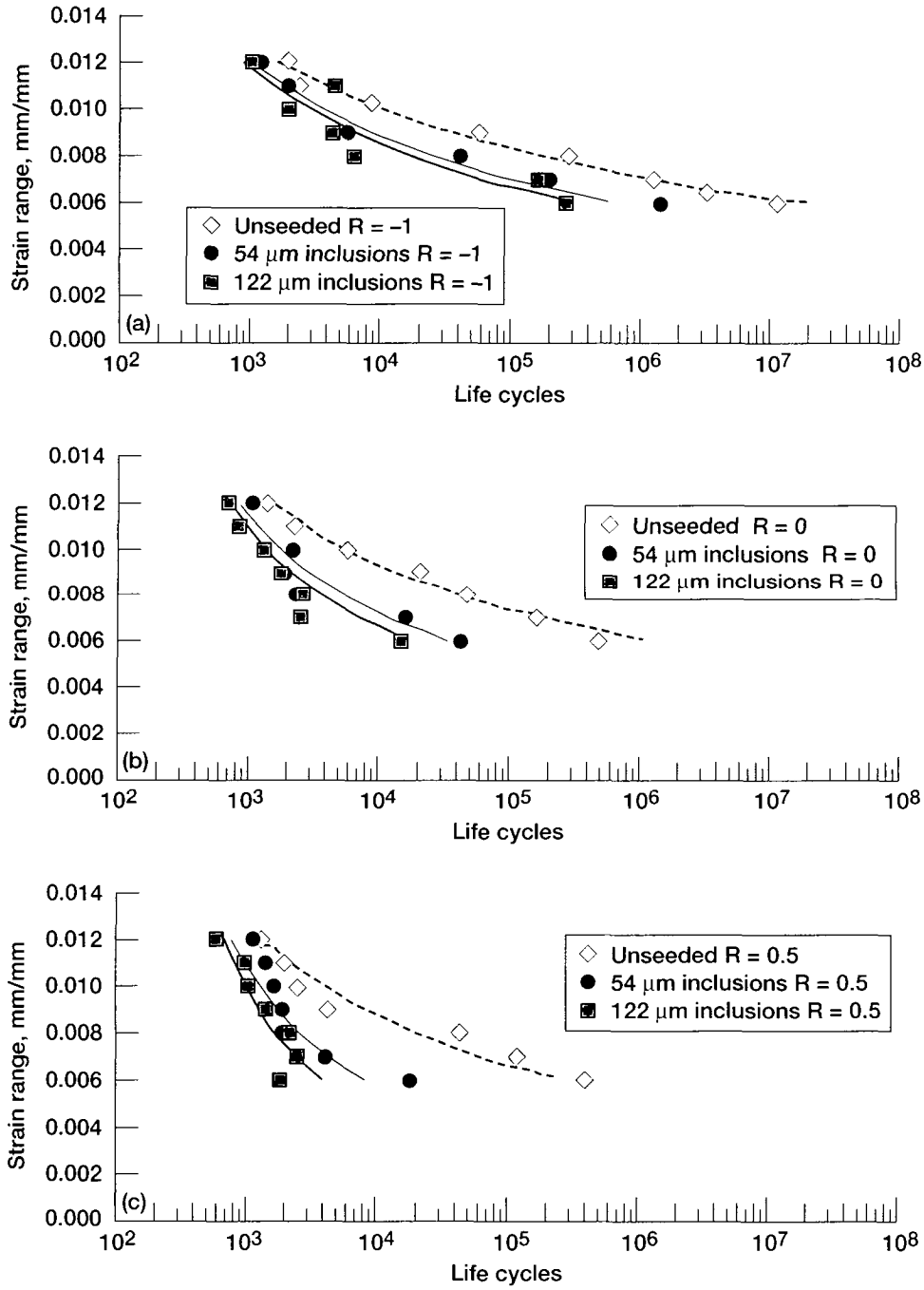

Figure 3.—LCF lives of unseeded versus seeded disk specimens. Estimates of the regression model are also shown. (a) $R_\epsilon = -1$. (b) $R_\epsilon = 0$. (c) $R_\epsilon = 0.5$.

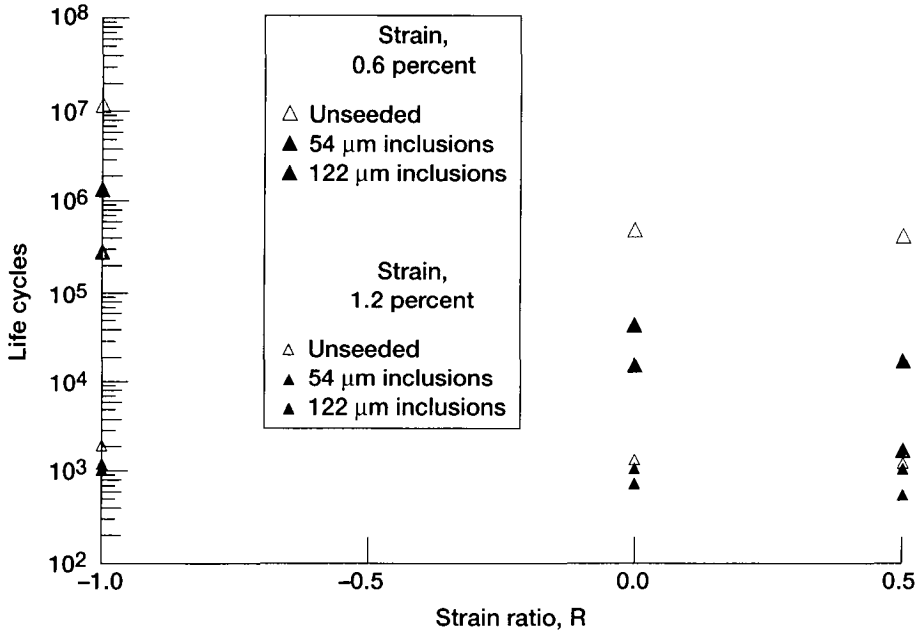

Figure 4.—Fatigue life versus strain ratio at strain ranges of 0.6 and 1.2 percent.

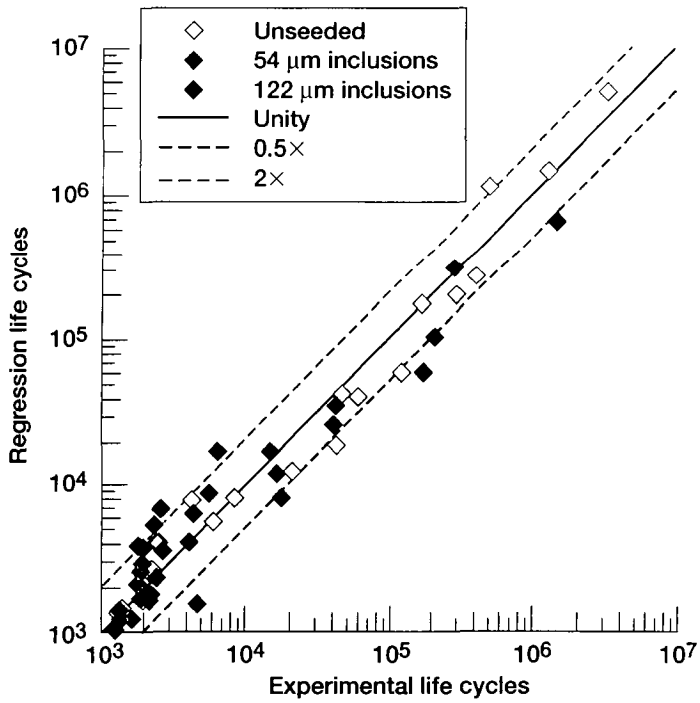

Figure 5.—Experimental versus regression estimated lives.

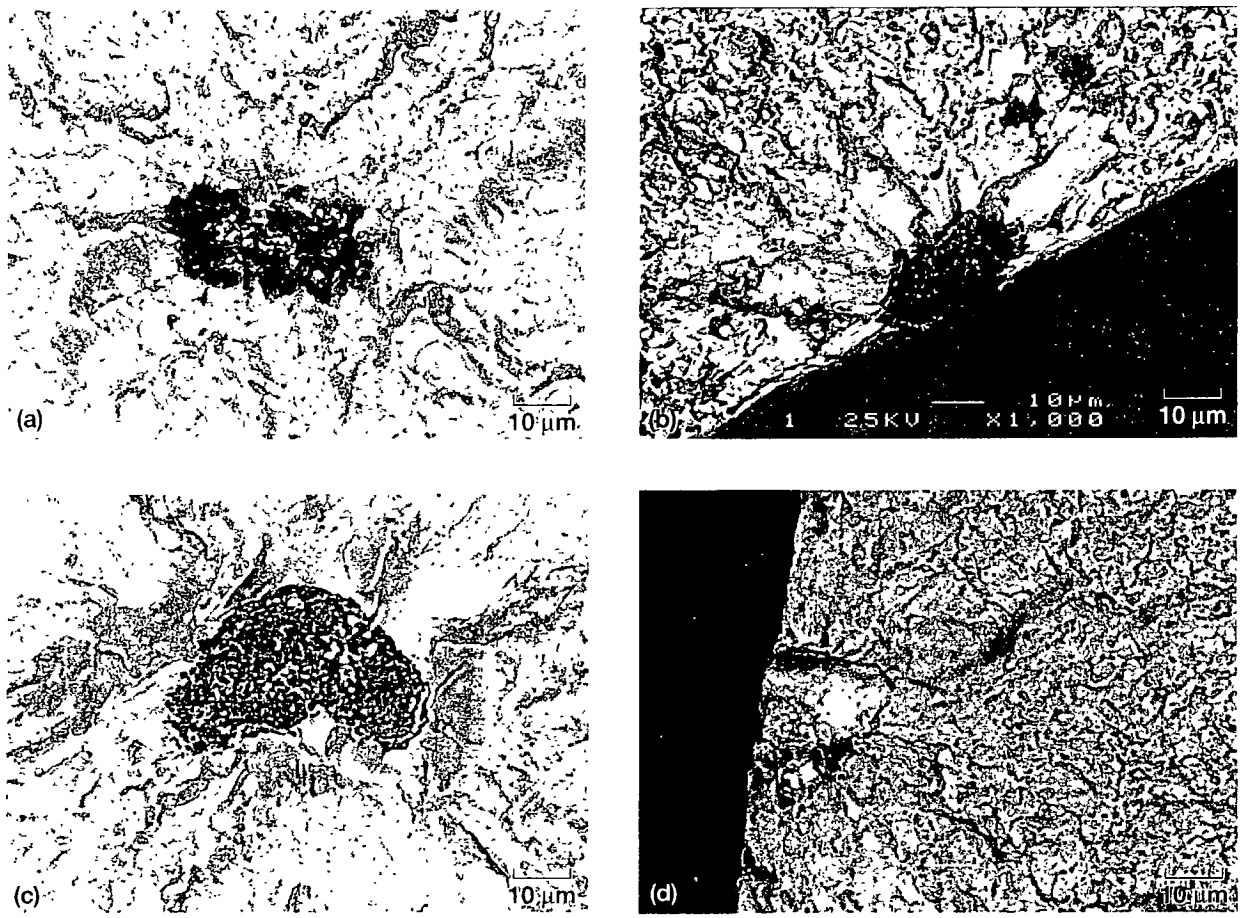

Figure 6.—Fatigue failure sites for unseeded disks. (a) 0.6 percent, $R_\epsilon = -1$, inclusion. (b) 1.2 percent, $R_\epsilon = -1$, inclusion. (c) 0.6 percent, $R_\epsilon = 0.5$, inclusion. (d) 1.2 percent, $R_\epsilon = 0.5$, micropore.

internal for lower strain ranges. Only single crack initiation sites usually caused specimen failure at lower strain ranges.

Typical fatigue failure sites of seeded specimens are shown in figures 7 and 8 for the material with 54 and 122 µm inclusions, respectively. A large majority of these specimens failed from cracks initiated at surface inclusions. Energy dispersive x-ray analysis of these inclusions indicated they had the same composition and similar size as the seeds and could be assumed to be the seeds. Cracks were sometimes initiated from several of these seeded inclusions at high strain ranges. Specimens tested at lower strain ranges invariably failed from a single crack initiation at an inclusion intersecting the surface or located at a depth less than the inclusion length in from the surface. The small inclusions initiating cracks appeared to be more granulated and broken up than the larger inclusions. However, the large inclusions also were usually at least partially cracked. The crack-initiation mechanism appeared similar for the small and larger seeds.

A probability plot comparing the projected areas of inclusions initiating cracks in the unseeded and seeded specimens versus the projected areas of inclusions extracted from each powder blend is shown in figure 9. The size distribution of inclusions initiating cracks to cause failure was comparable to the overall size distribution of the inclusions within each seeded powder blend. So while increasing seeded inclusion size reduced LCF life when comparing between the two seeded materials within each seeded material, apparently the relatively few inclusions intersecting the specimen surface limited life rather than the largest inclusion captured within the entire specimen volume. This is consistent with the debit in life previously observed for surface-initiated failures in general (ref. 1). The reasons that surface-connected

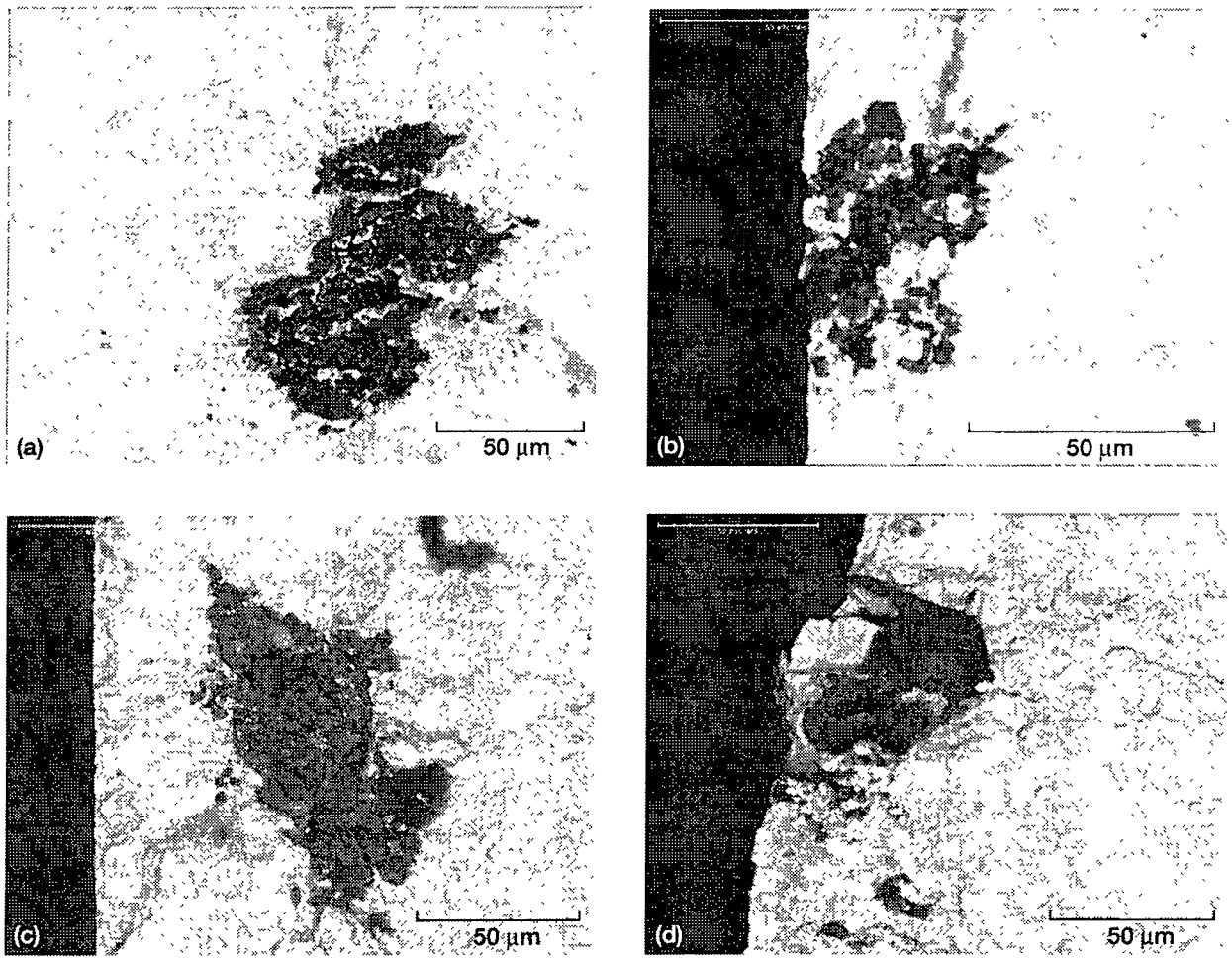

Figure 7.—Fatigue failure sites for disks seeded with 54 μm seeded inclusions. (a) 0.6 percent, $R_\epsilon = -1$, single internal-seeded inclusion initiation. (b) 1.2 percent, $R_\epsilon = -1$, typical of three surface-seeded inclusion initiations. (c) 0.6 percent, $R_\epsilon = 0.5$, single near-surface inclusions. (d) 1.2 percent, $R_\epsilon = 0.5$, typical of two surface-seeded inclusion initiations.

inclusions limit life in this way are currently being carefully studied using interrupted testing and detailed metallographic evaluations. Furthermore, a comparison of the effects of different inclusion morphology at the same size would be necessary to separate any possible additional effects on life associated with the granulated versus singular nature of the small and large seeds, respectively.

Remaining Issues

The resulting relationship can be applied using a probabilistic inclusion simulation approach to model the probability of a known density of inclusions having a known inclusion size distribution to intersect the surface of a known stressed volume and the resulting effect on fatigue life at 650 °C. However, a series of important issues need to be explored through additional testing in order to more fully assess inclusion effects on fatigue life and to realistically estimate their effects on the fatigue life of turbine disks:

(1) The temperature dependence of these inclusion effects on fatigue life must be determined. Disk webs and bores usually operate at temperatures several hundred degrees cooler than the typical

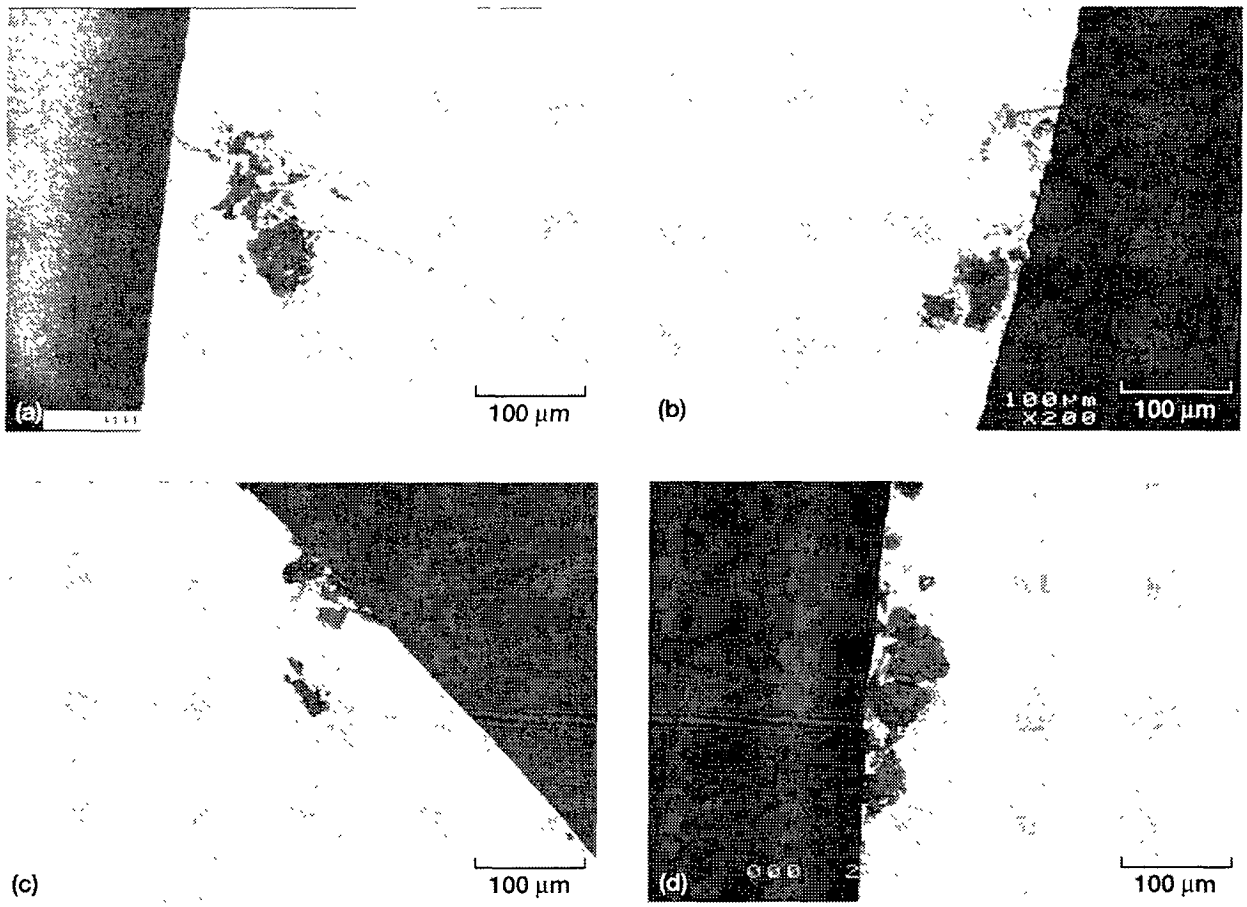

Figure 8.—Fatigue failure sites for disk seeded with 122 μm seeded inclusions. (a) 0.6 percent, $R_\epsilon = -1$. (b) 1.2 percent, $R_\epsilon = -1$. (c) 0.6 percent, $R_\epsilon = 0.5$. (d) 1.2 percent, $R_\epsilon = 0.5$.

maximum rim temperature of 650 °C chosen for this study. These sections of the disk take up a significantly larger volume than the rim and would therefore be expected to capture a wider distribution of inclusion sizes and orientations. The effects of inclusions on fatigue life in these sections must be established.

(2) The cyclic history and processes of crack initiation and propagation at inclusions need to be separated through interrupted testing. This would allow modeling of the fatigue cycles necessary for cracks to initiate and the cycles of subsequent cyclic crack propagation at inclusions of varying dimensions, orientations, and locations.

(3) The comparative lives of failures initiating from surface and from internal inclusions need to be fully assessed. The results could reflect previous findings that surface-initiated failures produce shorter lives than internally initiated failures. However, direct comparisons of surface versus internal inclusion-initiated failures are necessary.

(4) The effects of surface enhancement processes such as shot peening on fatigue cracking at surface inclusions must be incorporated. These surface treatments are usually applied to disks. The resulting compressive residual stresses produced by such treatments could retard or fully prevent cracking at surface inclusions, possibly increasing fatigue life.

(5) The effects of other disk-machining processes and more realistic features on cracking at inclusions then need to be brought in. Disks are machined by point turning, milling, broaching, drilling, as well as grinding. Each of these processes can produce different damage and residual stresses near the surface, and could affect the fatigue-cracking process. A real disk feature such as

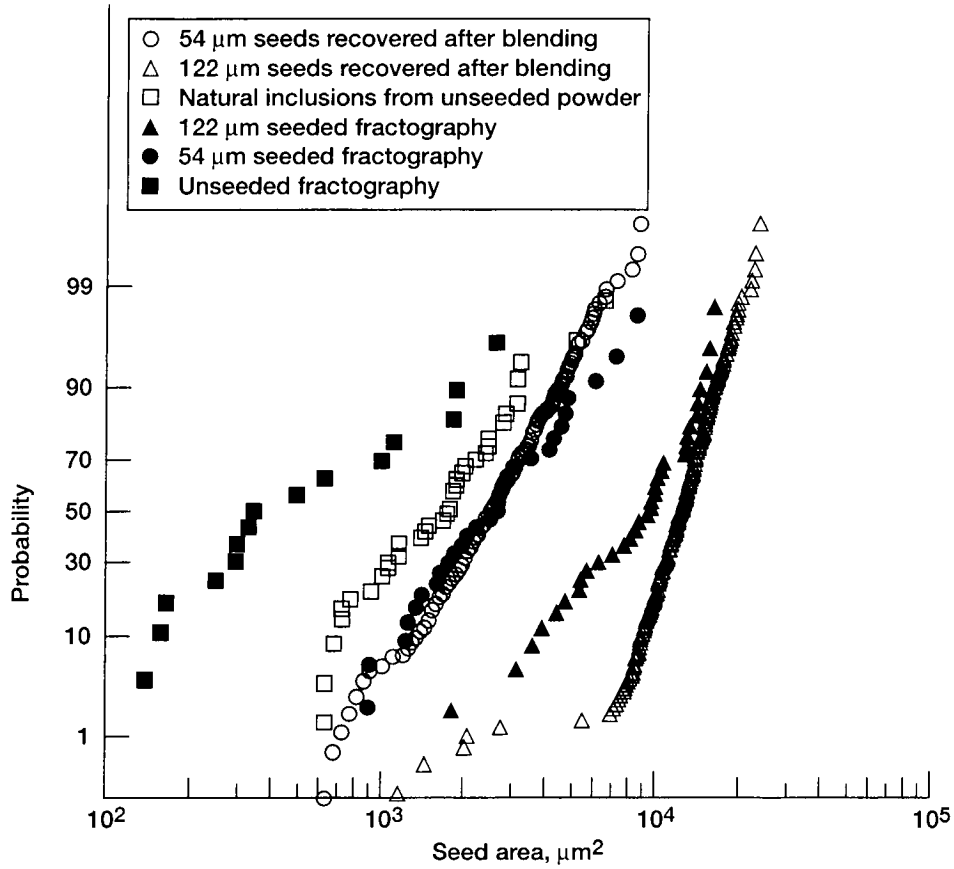

Figure 9.—Probability plot comparing the size distributions of the input seeds and inclusions initiating failure in the LCF unseeded and seeded specimens.

a hole or blade slot is also subjected to a more complex stress state than the conventional uniaxial fatigue specimens tested here. These disk features could respond very differently in crack initiation and propagation at inclusions.

(6) The effects of realistic disk volumes and surface areas on cracking at inclusions then need to be evaluated to scale up the life model's predictions to real disks. Larger volumes and surface areas of real disks capture more inclusions of a wider range in size, orientation, and location. Spin testing of seeded disks is necessary to calibrate a disk life model generated through conventional and disk feature specimens to model the life of a real disk shape.

Summary and Conclusions

In summary, the effects of inclusions on fatigue life in a nickel-based disk superalloy, Udimet 720, were successfully investigated. Elevated quantities of seeded inclusions were introduced during powder metallurgy processing of the material. Multiple strain-controlled fatigue tests were performed at 650 °C. Analyses were performed to compare the LCF lives and failure initiation sites as functions of inclusion content and fatigue conditions.

A large majority of the failures in specimens with introduced inclusions occurred at cracks initiating from inclusions at the specimen surface. The inclusions reduced mean fatigue life by up to about 100×. The reduction in life was found to be dependent on inclusion size, inclusion density, strain range, and strain ratio. Tests at lower strain ranges and higher strain ratios of specimens with larger seeded inclusions produced larger reductions in life.

It can be concluded from this work that

(1) Nonmetallic inclusions can drastically reduce the fatigue life of nickel-based disk superalloys.
(2) Effects are dependent on inclusion size, inclusion density, strain range, and strain ratio.
(3) Important issues involving inclusion effects including temperature dependence, crack initiation versus propagation, surface treatments, realistic disk features and machining, and realistic disk spin testing need to be addressed in order to accurately model inclusion effects on disk fatigue life.

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13. ABSTRACT ***(Maximum 200 words)***
The fatigue lives of modern powder metallurgy (PM) disk alloys are influenced by variabilities in alloy microstructure and mechanical properties. These properties can vary due to the different steps of materials/component processing and machining. One of these variables, the presence of nonmetallic inclusions, has been shown to significantly degrade low-cycle fatigue (LCF) life. Nonmetallic inclusions are inherent defects in powder alloys that are a by-product of powder-processing techniques. Contamination of the powder can occur in the melt, during powder atomization, or during any of the various handling processes through consolidation. In modern nickel disk powder processing facilities, the levels of inclusion contamination have been reduced to less than 1 part per million by weight. Despite the efforts of manufacturers to ensure the cleanliness of their powder production processes, the presence of inclusions remains a source of great concern for the designer. The objective of this study was to investigate the effects on fatigue life of these inclusions. Since natural inclusions occur so infrequently, elevated levels of inclusions were carefully introduced in a nickel-based disk superalloy, Udimet® 720 (registered trademark of Special Metals Corporation), produced using PM processing. Multiple strain-controlled fatigue tests were then performed on this material at 650 °C. Analyses were performed to compare the LCF lives and failure initiation sites as functions of inclusion content and fatigue conditions. A large majority of the failures in specimens with introduced inclusions occurred at cracks initiating from inclusions at the specimen surface. The inclusions could reduce fatigue life by up to 1003. These effects were found to be dependent on strain range and strain ratio. Tests at lower strain ranges and higher strain ratios produced larger effects of inclusions on life.

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