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Effects of High-Temperature Exposures on the Fatigue Life of Superalloy Udimet® 720

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Abstract

The purpose of this study was to examine the effects of extended exposures on the near-surface fatigue resistance of a disk superalloy. Powder metallurgy processed, supersolvus heat-treated Udimet® 720 (U720) fatigue specimens were exposed in air at temperatures from 650 to 705 °C for 100 hr to over 1000 hr. They were then tested using conventional fatigue tests at 650 °C to determine the effects of exposure on fatigue resistance. The exposures reduced life by up to 70 percent and increased the scatter in life, compared to unexposed levels. Fractographic evaluations indicated the failure mode was shifted by the exposures from internal to surface crack initiations. The increased scatter in life was related to the competition between internal crack initiations at inclusions or large grains producing longer lives, and surface crack initiations at an environmentally affected surface layer producing shorter lives.

Introduction

Low-cycle fatigue (LCF) tests conventionally used to characterize the LCF resistance of disk superalloys are usually performed at cyclic frequencies of 0.33 Hz or faster, in the interest of time and cost. However, service conditions for disks in some aerospace and land-based gas turbine engines can produce major cycle periods extending from minutes to hours to days. Over a service life, this can produce total service times exceeding 1000 hr for aerospace applications and 100 000 hr for land-based applications. The costs of running strain-controlled LCF tests in this manner would be prohibitive from both time and cost considerations. However, some aspects of the surface effects of realistic total exposure times can be considered economically.

Time-dependent effects of realistic mission cycles on fatigue resistance can be significant in superalloy disks. Earlier studies have shown that specimen fatigue tests, which have dwell times included within each cycle, can give lives significantly degraded from test cycles using conventional frequencies of 0.33 to 0.5 Hz (refs. 1 to 6). However, strain-controlled tests with strain dwells at maximum strain can allow relaxation of maximum cyclic stresses (ref. 7). This reduction in cyclic stress can counterbalance some of the creep and environmental damage produced by service dwell times. Such stress relaxation can be exaggerated over that possible in real disks in service, which have large, elastically constrained volumes. A disk cannot be allowed to creep significantly due to very tight blade, clearance, and rotational constraints within a turbine engine rotor. The majority of a disk is therefore usually not subjected to stress-temperature conditions allowing creep over 0.1 to 0.2 percent during service life. However, the environmental exposures are present over the entire disk surface, and their effects on disk life need to be considered for accurate prediction of disk life. Extended exposures at elevated temperatures prior to conventional LCF testing has been shown to capture some of the effects of service environment in a cast blade alloy at 871 °C (ref. 8).

The purpose of this study was to examine the effects of extended exposures on the near-surface fatigue resistance of a disk superalloy. Powder metallurgy-processed, supersolvus heat-treated Udimet® 720 (U720) superalloy fatigue specimens were exposed in air at several potential maximum application temperatures of 650 to 704 °C for extended times. They were then tested using conventional fatigue tests at 650 °C to determine the effects of exposure on fatigue resistance.

Materials and Procedure

Material Processing

A U720 powder metallurgy disk was obtained courtesy of Solar Turbines from Wyman-Gordon Forgings. The powder was first atomized in argon and screened through a 150-mesh screen. It was then canned, hot isostatically pressed, extruded, and isothermally forged using typical conditions for this alloy (ref. 9). The forged pancake was then machined to a disk about 61 cm in diameter and 10-cm thick.

The disk was heat-treated at Wyman-Gordon Forgings on a steel tray in a gas-fired furnace. The solution heat treatment was performed at 1171 °C for 3 hr. The disk was then transferred in about 60 sec to a tank containing agitated oil held at a temperature of about 50 °C and oil quenched. The quenched disk was visually confirmed to be free of quench cracks. It was then aged at 760 °C/8 hr + 650 °C/24 hr, as typically performed on this alloy (ref. 9).

Exposures and Mechanical Testing

Specimens were extracted from the disk midsection away from all quenched surfaces in order to minimize any effects on mechanical properties of quenching rate variations at different specimen locations in the disk. The specimens had a gage diameter of 0.64 cm and length of 1.9 cm. Many of the fully machined specimens were first exposed in air as groups of five lying on a tray in a conventional resistance-heated furnace. Exposure temperatures at the fatigue testing temperature of 650 °C and at an elevated temperature of 704 °C were used for 100 and 1029 hr. A centerpoint exposure condition of 677 °C for 510 hr was also included. Fatigue tests were performed at 650 °C in closed-loop servo-hydraulic testing machines using induction heating and axial extensometers. Most baseline fatigue tests were performed in two stages to reduce total testing time. First, the test was conducted in strain control conditions using a triangular waveform to a total strain range of 0.7 percent and a strain ratio of $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = 0$, using a frequency of 0.33 Hz. After cycling for 24 hr, tests were continued to failure in load control conditions using a triangular waveform to achieve the same stabilized maximum and minimum loads as before, at a frequency of 10 Hz. Verification cyclic dwell fatigue tests were performed with strain controlled throughout the test using a triangular waveform with the same total strain range and strain ratio, but using a load cycle taking 20 sec followed by a dwell at 0 strain for 40 sec. The dwell was

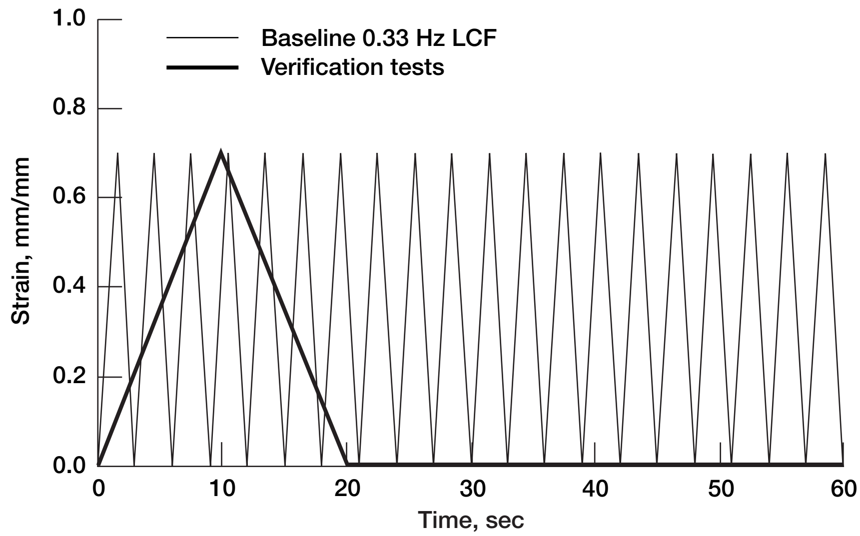

Figure 1.—Comparison of strain-time test waveforms.

performed at zero strain to prevent cumulative relaxation of the maximum cyclic stress due to the dwells. This gave a total cyclic dwell test time of 1 min per cycle. The strain versus time waveforms of baseline and verification fatigue tests are compared in figure 1. All tests were continued until failure.

Fractographic evaluations were performed on all specimens after failure to determine the crack initiation sites. Metallographic sections were prepared from one representative specimen for each exposure and testing condition. The sections were taken from the gage sections and oriented normal to the loading axis. Grain sizes were determined from selected specimens according to ASTM E112 linear intercept procedures using circular grid overlays.

Results and Discussion

Metallographic Characterizations

The typical microstructures of untested specimens are shown in figure 2. The material had a coarse grain size of ASTM 6.0 (45 μm) due to the supersolvus heat treatment. The grain boundaries displayed serrations due to the formation of relatively coarse γ'-precipitates during the relatively slow cooling of the deeply imbedded specimen blanks. The mean diameter of γ'-precipitates within the grains was about 0.4 μm.

Fatigue Test Results

Fatigue life is shown versus estimated cumulative probability to compare the effects of various exposures on subsequent LCF life in figure 3. Lives of exposed specimens were invariably lower than unexposed specimens, reducing mean life (arrow) by up to 70 percent. It can also be seen that exposed specimens had lower slopes on the probability plot, indicating more scatter and larger standard deviations than for unexposed specimens. Scatter plots of life versus exposure temperature and time are shown in figure 4.

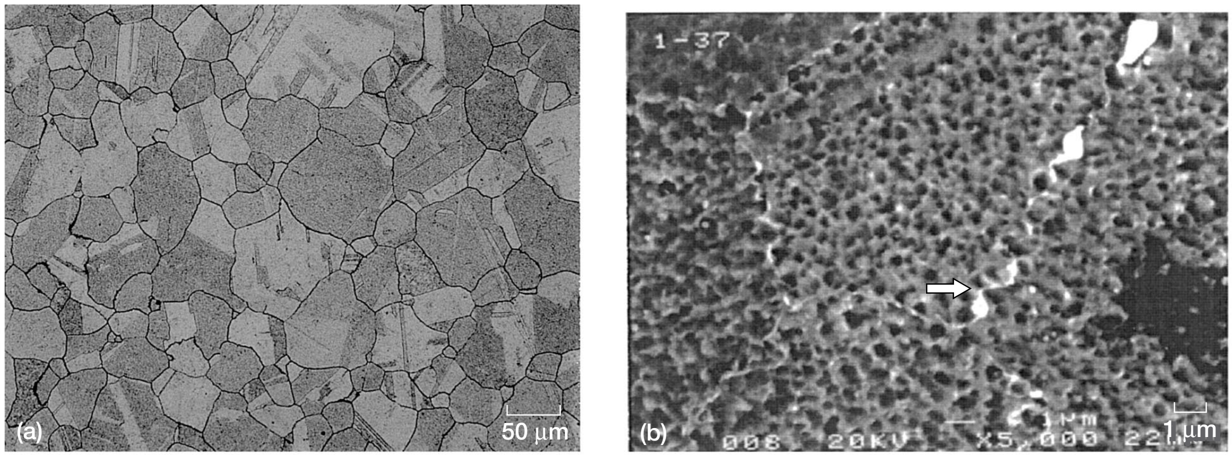

Figure 2.—Typical microstructures. (a) Grain size. (b) Serrated grain boundaries decorated with carbides (arrow).

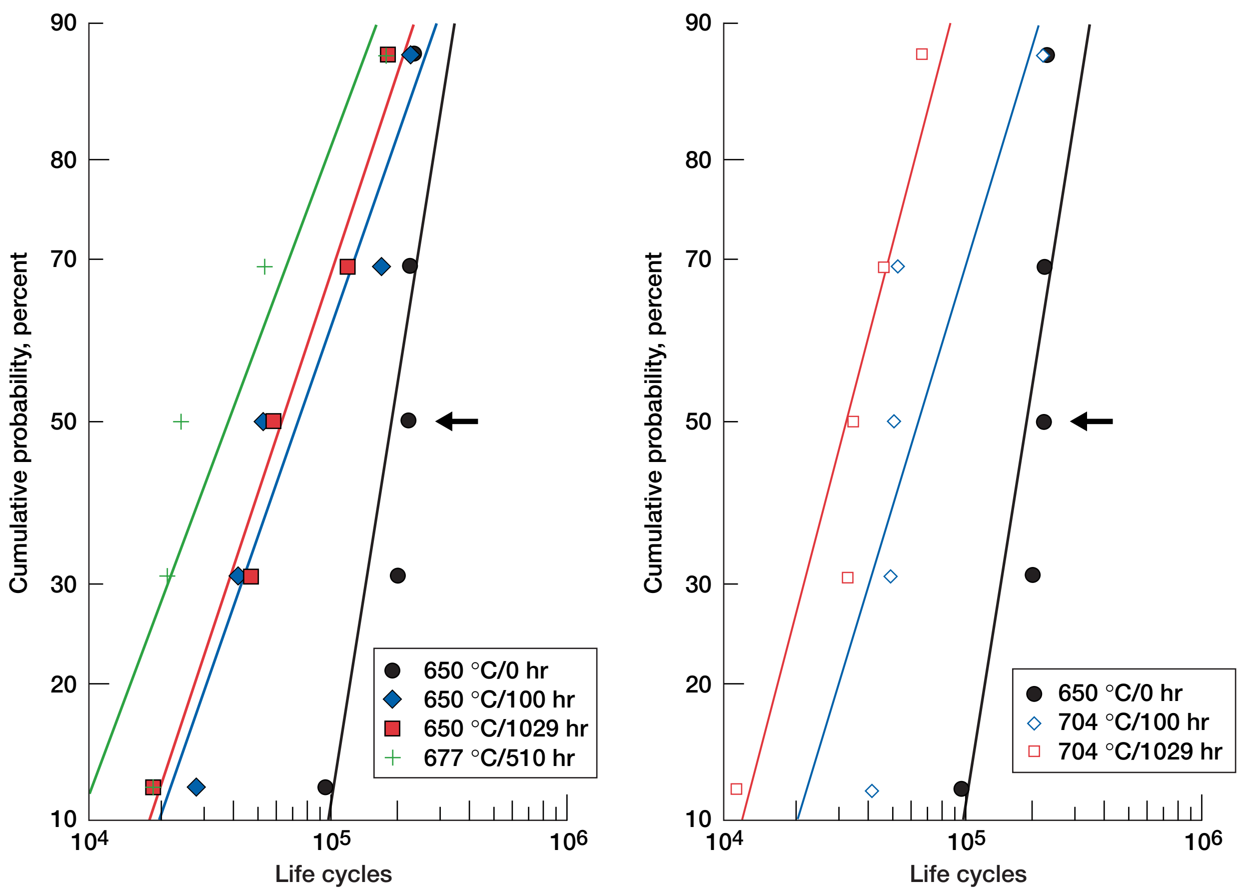

Figure 3.—Estimated cumulative probability versus fatigue life of exposed specimens (mean life indicated by arrows).

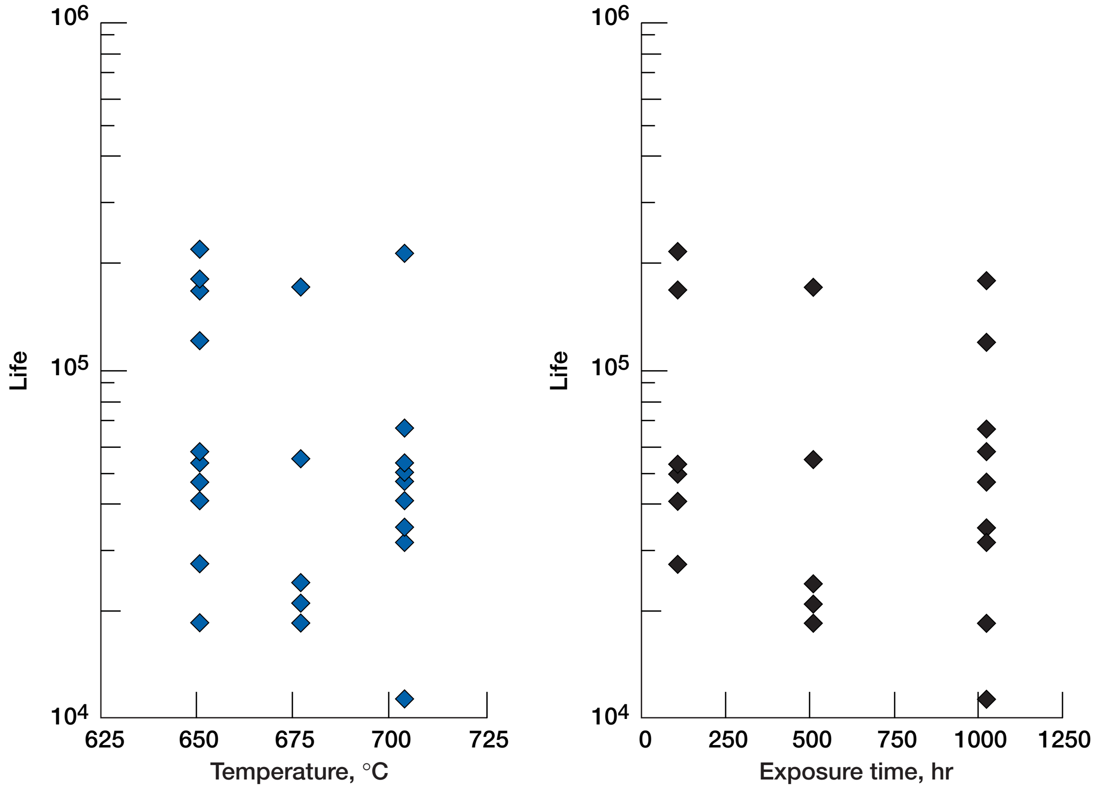

Figure 4.—Fatigue life versus exposure temperature and time.

A nonlinear regression model was generated using forward stepwise regression with the factors exposure temperature and log(time) to model fatigue life. The resulting relationship obtained had poor correlation and only included time

$$\log(\text{life}) = 4.9409 - 0.3174 \times t'$$

where $t' = (\log(\text{time}) - 1.5062)/1.506$. This gave a low adjusted correlation coefficient $R^2_{adj} = 0.307$ and root mean square (rms) error of 0.322.

Fatigue Failure Sites

Typical fatigue failure sites are compared in figures 5 to 6. Unexposed specimens failed from cracks initiating internally at large grains or at nonmetallic inclusions, as shown in figure 5. The large grains appeared to start cracks by failing on a single flat plane or "facet," presumably due to concentrated slip along a single slip band (ref. 7). The nonmetallic inclusions were predominantly composed of $Al_2 0_3$, and were presumably introduced during the powder production and handling processes before consolidation (ref. 6). Exposed specimens sometimes failed from cracks initiating internally at these above sites, but more often failed from cracks initiating at an environment-affected surface layer, especially for long exposure times. These cracks initiated and grew in a transgranular mode normal to the loading axis, as shown in figure 6.

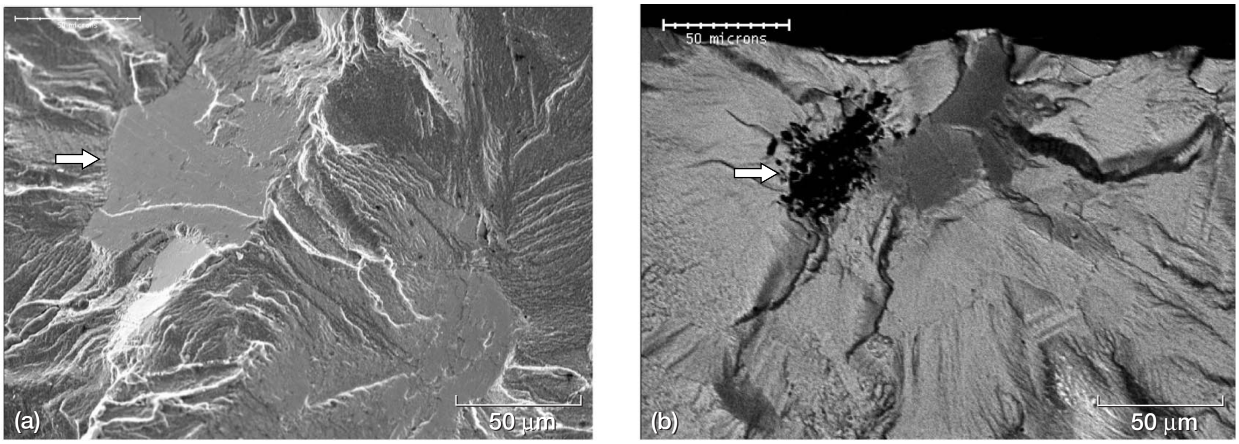

Figure 5.—Unexposed specimens tested at 650 °C. (a) Failing from internal large-grain facet giving longest life of 224 803 cycles. (b) Failing from near-surface alumina inclusion giving shortest life of 97 878 cycles.

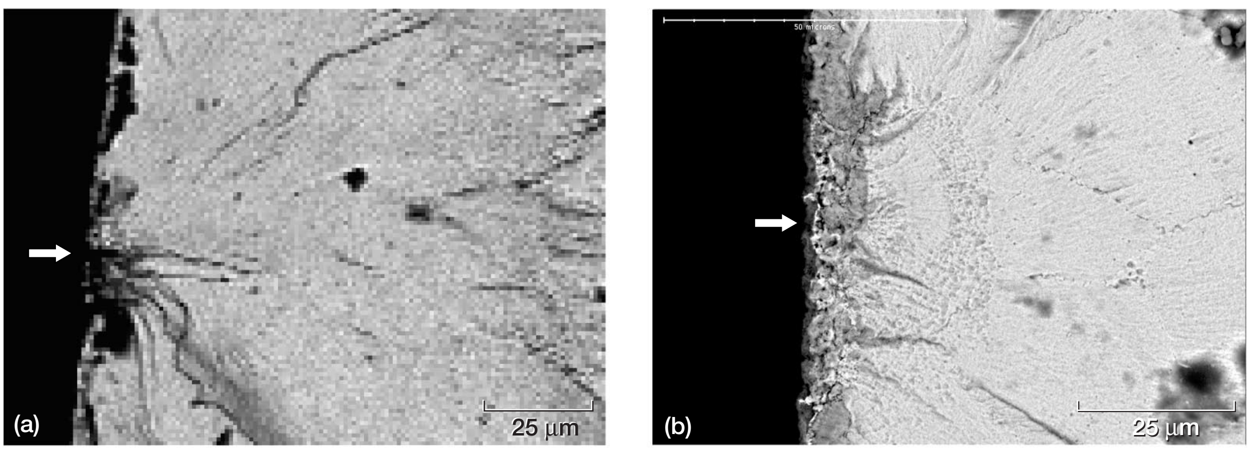

Figure 6.—Preexposed specimens failed from surface-initiated cracks. (a) After 650 °C/1029 hr giving life of 57 771 cycles. (b) After 704 °C/1029 hr giving life of 32 280 cycles.

These competing failure modes clearly accounted for the wide scatter in life of exposed specimens, as illustrated in the probability plot of figure 7. Specimens failing from internal cracks initiating at grain facets or inclusions had relatively long lives for each condition, comparable to unexposed lives. Specimens failing from cracks at the surface layer had relatively short lives and could be combined into one population. Life plotted versus depth of the failure initiation point indicated a strong correlation, as shown in figure 7. A nonlinear regression model was generated using forward stepwise regression of the factors exposure temperature, log(time), depth of the failure initiation point categorized as 0 for surface and 1 for internal initiations, and their interactive terms to model fatigue life. Some cross-correlations of exposure time with depth of the failure initiation point, and exposure temperature with depth were present, which prevented inclusion of all terms in the model. This indicated that increased exposure time and temperature increased the likelihood of promoting surface-initiated failures. However, depth of the failure initiation was found to be a far better predictor of life. The resulting relationship obtained was therefore only a function of depth, but it gave a much improved R^2_{adj} of 0.628 and an rms error of 0.236 compared to the previous exposure time-based regression:

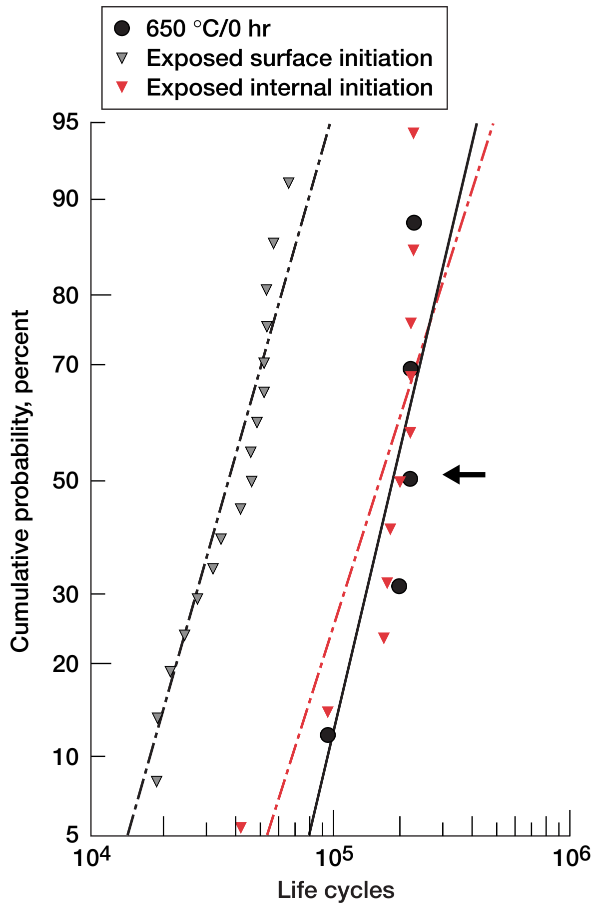

Figure 7.—Segregation of exposed specimens lives based on depth of failure initiation.

log(life) = 4.5798 if depth = surface
log(life) = 5.2108 if depth = internal

Transverse metallographic sections were prepared from representative specimens to compare the surface effects. As shown in figure 8, an oxidized surface layer predominantly made up of nickel oxide can be clearly seen in the exposed specimens. An additional zone with branched fingers of attack, rich in aluminum oxide, extended further in. The depth of the oxidized layer and the combined depth of the layer plus the attacked zone tended to increase with exposure temperature and exposure time. However, the surface oxide layer was too brittle to easily allow metallographic preparation for accurate measurements of oxide depth. Further metallographic work is underway to allow these measurements.

Verification Tests

In order to test the validity of using preexposures at the same or elevated temperatures to capture some effects of service exposures during cycles, two additional groups of tests were performed. Conventional cyclic tests were performed at 704 °C without prior exposures, in order to understand the effects of higher test temperature alone on inherent fatigue life. A cyclic dwell test was also performed at 650 °C to directly compare the effects of prior exposures to the effects of more realistic mixing of cyclic loading and exposures. The period of the cyclic dwell cycle was selected by simply dividing the longest exposure

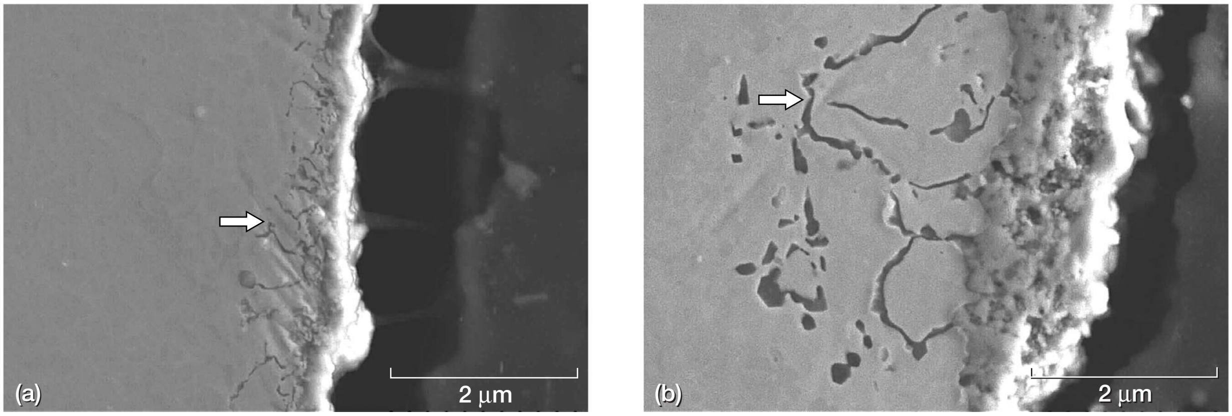

Figure 8.—Transverse metallographic sections of exposed specimens showing the environment-affected surface layer and alumina-rich fingers of attack (arrows) in exposed specimens. (a) After 650 °C/100 hr. (b) After 704 °C/1029 hr.

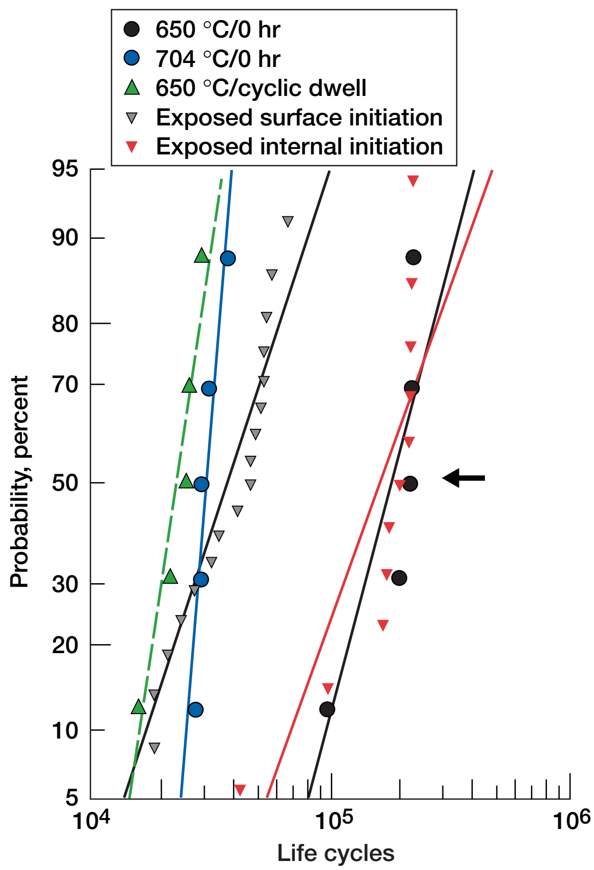

Figure 9.—Comparison of unexposed lives at 650 and 704 °C exposed lives and lives of tests at 650 °C having cyclic dwells.

time at 650 °C for 1029 hr by the observed subsequent log mean life of 64 021 cycles. This gave an overall cycle period of 1 min, as shown in figure 1. Within each cycle, a strain cycle of 0.7 percent with $R_\varepsilon = 0$ was first applied to reproduce that of the conventional subsequent LCF tests. A dwell at zero strain was then applied to introduce exposure effects. The dwell was performed at zero strain rather than maximum strain, to prevent likely cumulative relaxation of the cyclic maximum stress from stress values of the conventional LCF tests.

The life results are compared to the previous results in the probability curves of figure 9. The unexposed 704 °C tests produced lives of 27 730 to 37 782 cycles, while the cyclic dwell tests produced lives of 16 054 to 29 204 cycles. These lives were comparable to those of exposed specimens having surface-initiated failures. Fractographic evaluations indicated the unexposed 704 °C tests and cyclic dwell tests specimens all had surface-initiated failures from the environment-affected surface layers (figs. 10 and 11).

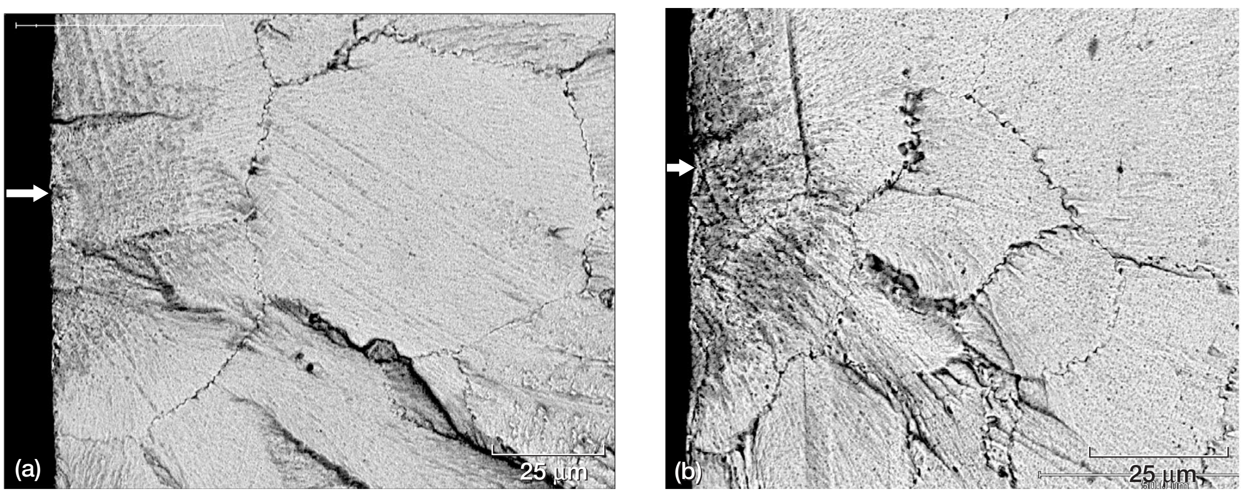

Figure 10.—Surface failure initiation sites for specimens tested at (a) 704 °C unexposed producing life of 29 333 cycles and (b) 650 °C with cyclic dwell producing life of 25 499 cycles.

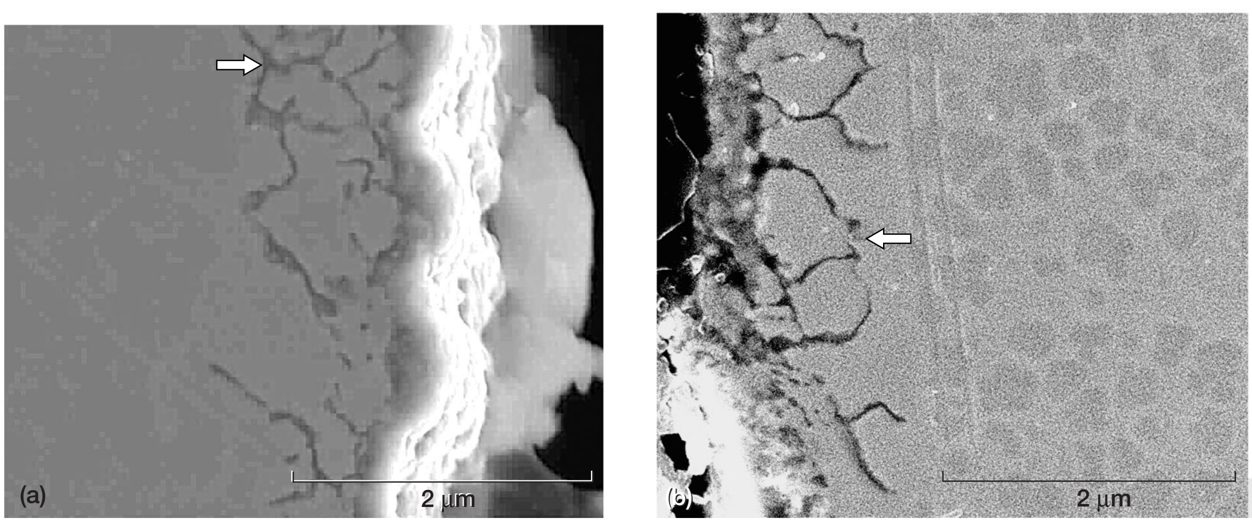

Figure 11.—Transverse metallographic sections of exposed specimens showing the environment-affected surface layer and alumina-rich fingers of attack (arrows). (a) After 704 °C unexposed LCF producing a life of 29 333 cycles. (b) After 650 °C with cyclic dwell producing life of 25 499 cycles.

Conclusions

In summary, prior exposures significantly affected fatigue life. The exposures reduced life and increased the scatter in life, compared to unexposed levels. Fractographic evaluations indicated the failure mode had shifted by the exposures from internal to surface crack initiations. The increased scatter in life was related to the competition between internal crack initiations at inclusions or large grains producing longer lives, and surface crack initiations at an environment-affected surface layer producing shorter lives. The surface crack initiations and associated shorter lives did successfully mimic that observed in more realistic cyclic dwell fatigue tests, as well as in tests at higher temperatures.

It can be concluded that prior exposures can be used to help approximate some aspects of service exposure effects. The exposures accomplish this by shifting to some degree the probable failure initiation site to the environment-affected surface layer, as in cyclic dwell tests. This produces a significantly lower life than for internally initiated failures observed in conventional low-cycle fatigue (LCF) tests. Therefore, it is necessary to screen and select sufficiently long exposure times that can induce this surface-failure initiation mode. It would then be necessary to segregate the resulting lives of exposed specimens according to the failure initiation site. The lives corresponding to surface-initiated failures can reasonably approximate cycle dwell life, at least for the cyclic dwell tests of this study. Lives corresponding to internally initiated failures should be considered separately. These internally initiated failures could in some cases approximate exposure effects associated with microstructural instabilities and defects, rather than environmental effects.

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13. ABSTRACT ***(Maximum 200 words)***

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