Effects of Temperature and Frequency on the HCF Behavior of a Ni-based Superalloy

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ABSTRACT

The objective of this research was to investigate the effects of temperature and frequency on the high cycle fatigue behavior of a single crystal superalloy using an ultrasonic fatigue system. Fatigue testing up to 10^9 cycles under fully reversed loading was performed at a temperature of 593 ºC (1100 ºF) to determine the ultra-high cycle fatigue behavior of PWA1484 at elevated temperature. Endurance limit results were compared to similar data generated on conventional servohydraulic test systems to determine if there are any frequency effects. Scanning electron microscopy was then used to determine the initiation sites and the failure mechanisms. Initial results indicate little or no frequency effect on the fatigue strength or failure mechanisms of PWA 1484 at 1100 ºF.

KEYWORDS: *superalloy, high cycle fatigue, ultrasonic*

1. INTRODUCTION

Recent work [1-3] using ultrasonic test systems has shown that many materials exhibit a sharp decrease in fatigue strength between fatigue lives of 10^6 and 10^9 cycles. This is in contrast to the classical fatigue limit, which assumes a constant minimum fatigue strength below which a material is assumed to have an infinite life (normally assumed equal to the fatigue strength at 10^6 or 10^7 cycles).

Recent changes to the Engine Structural Integrity (ENSIP) handbook [4], the Air Force manual used to provide guidance to the engine manufacturers, require that engine components subjected to high cycle fatigue

Morrissey, R.J.; Golden, P.J. (2005) Effects of Temperature and Frequency on the HCF Behavior of a Ni-based Superalloy. In *Evaluation, Control and Prevention of High Cycle Fatigue in Gas Turbine Engines for Land, Sea and Air Vehicles* (pp. 32-1 – 32-10). Meeting Proceedings RTO-MP-AVT-121, Paper 32. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

be designed to meet lifetime requirements of 10^9 cycles (as opposed to the previous guideline of 10^7 cycles). Specifically, ENSIP states, "All engine parts should have a minimum HCF life of 10^9 cycles. This number is based on the observation that an endurance limit does not exist for most materials." Due to cost and time constraints, it is impractical to assume that conventional testing methods can be used to gather the experimental data necessary to understand the material behavior in this regime. Ultrasonic fatigue testing at 20 kHz offers an alternative testing method for generating the data necessary at very long fatigue lives.

In addition, it provides a method for determining potential frequency effects that may be important in engine applications where components can experience vibratory loading in the kilohertz regime. A large decrease in fatigue strength in the ultra-high cycles fatigue regime, due either to the lack of a classical fatigue limit or to a decrease in strength caused by strain rate effects, could have a major impact on turbine engine design.

2. EXPERIMENTAL PROCEDURE

Material

The test material was a Ni-based single crystal, PWA1484, which was developed by P&W for turbine engine airfoil applications. It is a precipitation strengthened cast mono grain nickel alloy based on the Ni-Cr-Al system. The material is characterized by continuous primary dendrites, which span the casting in the direction of solidification. Secondary dendrite arms, perpendicular to solidification, define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> family directions. A more detailed description of the material microstructure can be found elsewhere [5].

Ultrasonic Test System

An ultrasonic fatigue system was used to determine the fatigue limit of materials out to 10^9 cycles. The main component of the ultrasonic system is a piezoelectric transducer, which converts an electronic signal at a frequency of 20 kHz ($\pm$ 500 Hz) into a mechanical displacement at the same frequency. The electronic signal is supplied by a power supply that automatically tunes to the natural resonant frequency of the system. If the frequency falls outside the 19.5-20.5 kHz range, the system shuts off automatically.

Attached to the transducer are a titanium booster and horn, which served to amplify the mechanical displacement. A specimen designed to run in resonance with the system is then attached to the horn. For elevated temperature testing, a lambda rod is attached between the horn and specimen to prevent the titanium horn from getting too hot. The specimens used in this study were cylindrical dogbones with a gage section diameter of 4 mm. The specimens were designed so that the maximum strain is located in the gage section. The specimen dimensions are shown in Figure 1. The threaded end of the specimen is attached to the horn. The other end of the specimen is a free surface for ultrasonic testing under fully reversed loading conditions. A thorough review of the ultrasonic testing technique for fatigue and fracture applications can be found in [6,7].

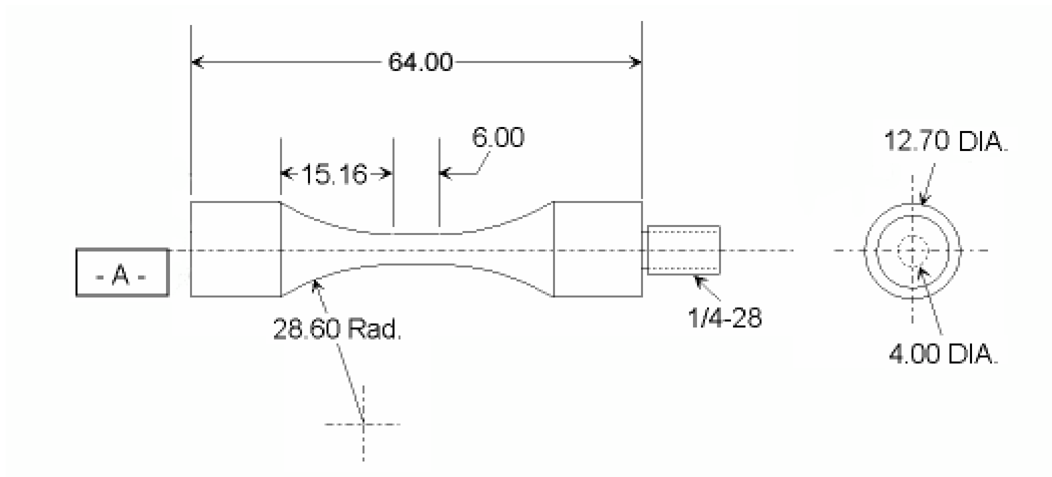

Figure 1: Ultrasonic Fatigue Specimen (all dimensions shown in mm).

Dynamic Analysis

The ultrasonic test setup was modeled using the finite element software STADYN, which was written for the static and dynamic analysis of structures. The problem was modeled dynamically using 1-D rod elements. As described previously, the structure for the fully reversed test was made up of a booster, horn, lambda rod, and the specimen. Figure 2 has a plot of the profile of the geometry used in the model. Each rod element in the model had an area property that is equal to the average value over the length of the structure that the element represents. The mesh was therefore more refined near locations of changing area and in the gage section of the specimen. Forty-one total rod elements were used with 15 of these elements in the specimen gage section. This was found to result in a converged solution. The entire structure was made of titanium and therefore each element used the material properties of Young's modulus E = 125.3 GPa at room temperature and 108.2 GPa at 593 ºC. The boundary conditions of the model were fixed-free. The structure was fixed at the center point of the booster (X = 0), which was a displacement node in the system. This was also the location where the booster was physically clamped to the test frame. The end of the specimen (X = 264 mm) was modeled as free.

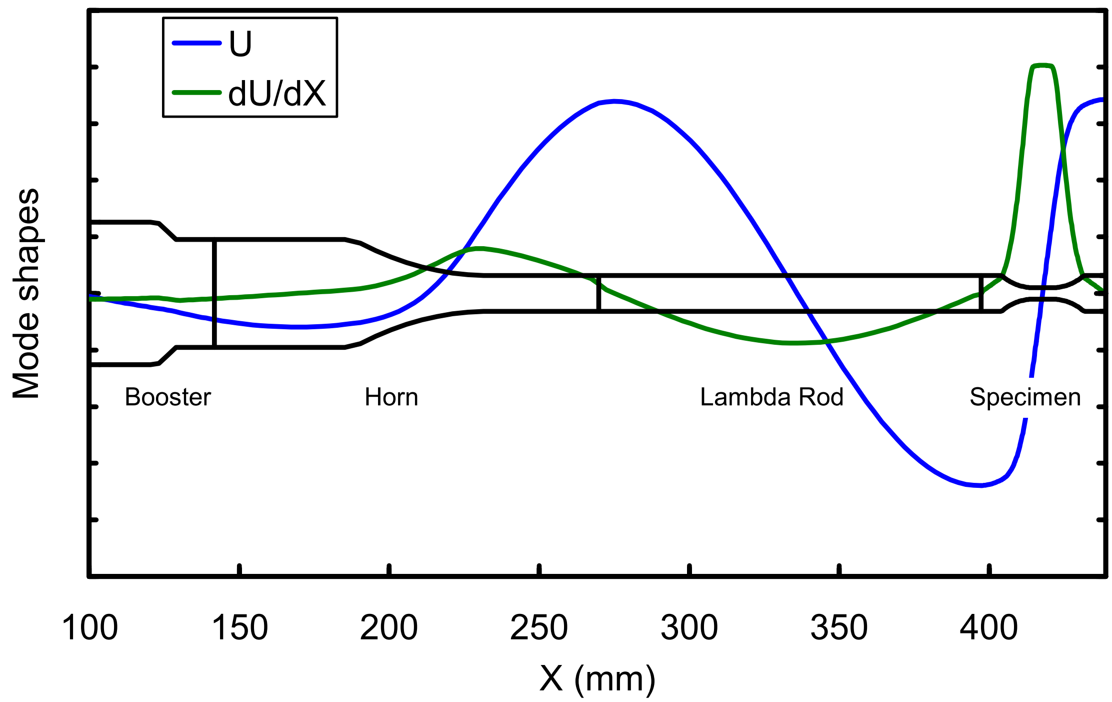

Figure 2: Displacement and strain mode shapes superimposed on test system profile.

The results of the vibration analysis for the fixed-free system are plotted in Figure 2. The solid line represents the geometry of the booster, horn, lambda rod and specimen (from left to right). The displacement mode shape, u(x), shown is from the 3rd mode, which has a resonant frequency of 20,700 Hz according to the model. The actual experimentally measured resonant frequency for this geometry was 20,250 Hz, a difference of about 2%. The mode shape shows displacement nodes at the fixed end, at a point within the horn, and at the center of the specimen gage section. The axial strain, $\varepsilon_x = du/dx$, is also plotted in Figure 2. Two important observations can be made from these curves. First, the ends of the specimens are strain (stress) nodes. One end of the specimen is free so it must be stress free, and the end of the specimen that joins the booster has a very low stress. Second, the gage section of the specimen not only has the peak strain but it has nearly constant strain over the entire gage length with only a 0.2% variation according to the analysis results. The strain decreases rapidly outside the gage section.

Calibration

In this study, all testing was performed at a stress ratio, R, of –1.0. Prior to each test, the displacement at the free end of the specimen is calibrated at room temperature with a strain gage bonded to the gage section. A room temperature calibration is performed because the strain gages cannot be used at temperatures of 1100 F. Under the nominally elastic conditions used for loading to very high cycles, there is a linear relationship between the displacement at the end of the specimen and the strain in the gage section. Following this calibration, a finite element model is used to determine the change in displacement caused by the elevated temperatures based on the change in material modulus. A second calibration factor is determined which is used to correlate the strain in the gage section with the displacement during elevated temperature testing. The scaled displacement mode shape at room and elevated temperatures is shown in Figure 3.

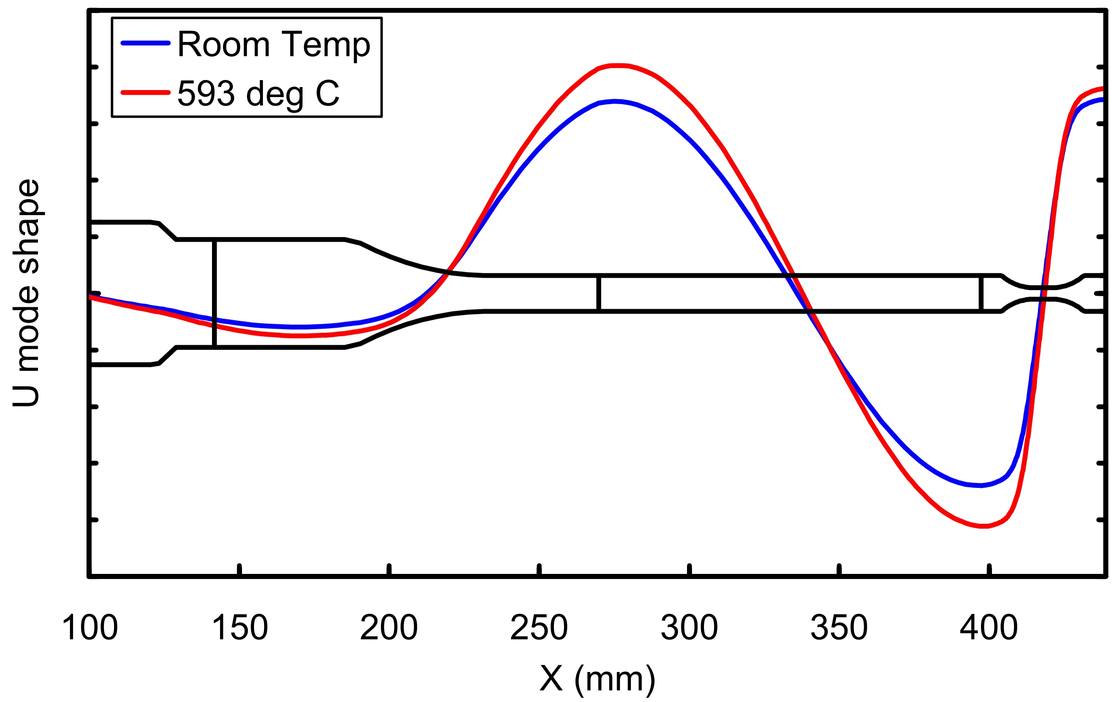

Figure 3: Displacement mode shape at room and elevated temperatures.

A high frequency fiber optic sensor is used to measure displacement at the free end of the specimen. The displacement, with the calibration factor from the strain gage and finite element model, is then used in a feedback loop during testing to actively control the strain, and therefore stress, in the gage section. The test control software continuously records the displacement and controls the output of the power supply and, therefore, indirectly controls the magnitude of the strain in the specimen.

Temperature Control

Specimens were heated during testing using a solid state induction heater. The induction heater was able to heat the gage section of the specimen uniformly (± 5 ºC) throughout the testing. This was done using a computer controlled feedback loop. An infrared pyrometer was used to monitor the temperature in the center of the gage section of the specimen. The pyrometer reading was used by the computer to control the induction heater output and keep the temperature constant.

An important consideration in ultrasonic testing is the heat that can be generated internally due to internal friction and damping. For some materials, this internal damping can lead to large temperature increases. For room temperature testing this can be very important, and care must be taken to minimize the effects of the damping. However, for elevated temperature testing, the internal damping is just a very small portion of the heat process (in conjunction with the induction heater). Since the specimen temperature is being continuously monitored, no additional precautions are necessary.

3. RESULTS

Experiments were performed under constant amplitude, fully reversed loading conditions. A stress of 400 MPa was chosen for the initial tests based on 10^7 cycle fatigue limit results from the National Turbine Engine HCF Program. These prior tests had been performed using the same PWA 1484 material on conventional servohydraulic (~60 Hz) test systems. A test was considered a run-out if it lasted 10^9 cycles. Failure occurred when a crack had grown large enough to decrease the natural frequency of the system below the standard operating range (19.5-20.5 kHz). Typical crack sizes at this point were at least 1 mm, or half of the specimen radius, and therefore the cycles to failure are considered total fatigue lives and not initiation lives. Maximum stresses ranging from 400 – 450 MPa were tested using the ultrasonic fatigue system.

The results of the testing are compared with the National HCF Program data in Figure 4. Although the 20 kHz data appear to be slightly below the 60 Hz data, all of the data is very consistent. Due to the limited amount of overlapping test data at both frequencies, no final determination can be made about a possible frequency effect. In addition, some limited testing during the HCF program at 60 and 900 Hz for R = 0.1 showed no apparent frequency effect. It is therefore likely that the apparent difference in fatigue strength between the 60 Hz and 20 kHz data is not due to a frequency effect.

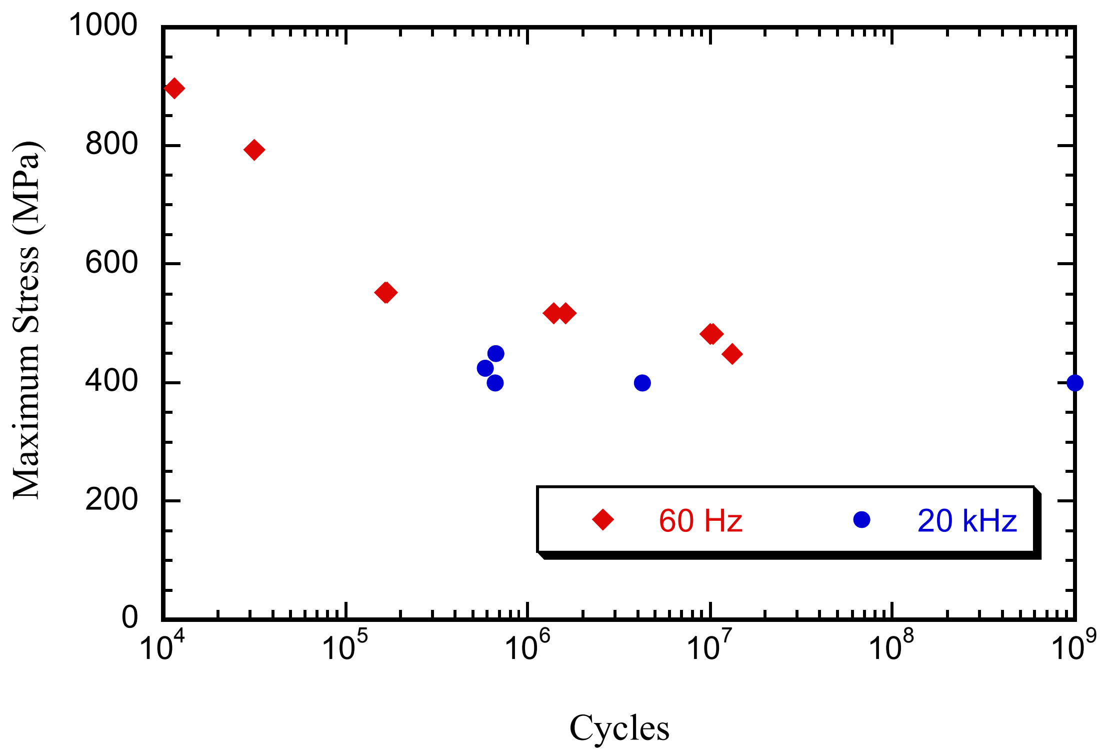

Figure 4: S-N curve for PWA 1484.

Figure 5 shows a typical fracture surface for PWA 1484 from conventional testing at 60 Hz performed during the HCF program. It was reported that the fatigue failures were highly crystallographic in nature and grew on one or more intersecting (111) type planes. The crack initiation points were mainly sub-surface, and seemed to be caused by carbide inclusions. This is consistent with the initial results obtained at 20 kHz using the ultrasonic fatigue system. Figure 6 shows a typical fracture surface using an optical microscope. As was the case in the previous program, the failure surfaces are crystallographic and grow on one or two intersecting planes. In addition, Figure 7 shows the same fracture surface as viewed with a scanning electron microscope (SEM). These pictures verify an internal initiation site very near the center of the specimen. In addition, Figures 7c and 7d show what appear to be carbides or non-metallic inclusions at the initiation site. These particles show up clearly in the backscattered image, Figure 7d.

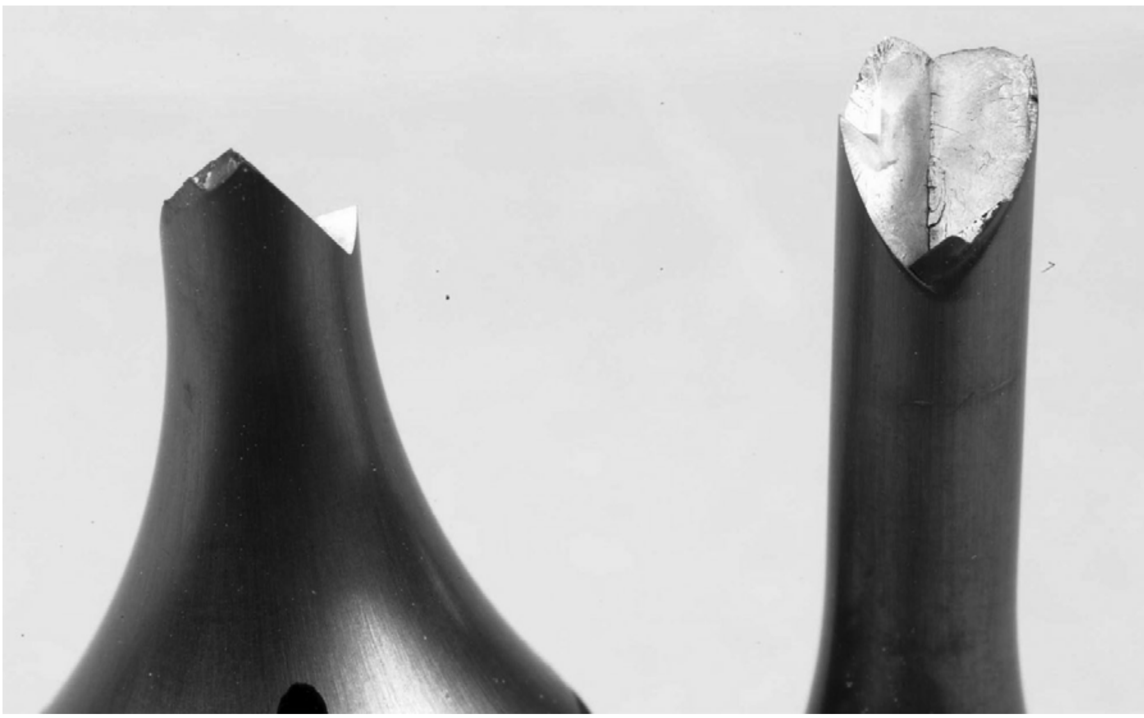

Figure 5: Fracture Surface of PWA 1484 (60 Hz).

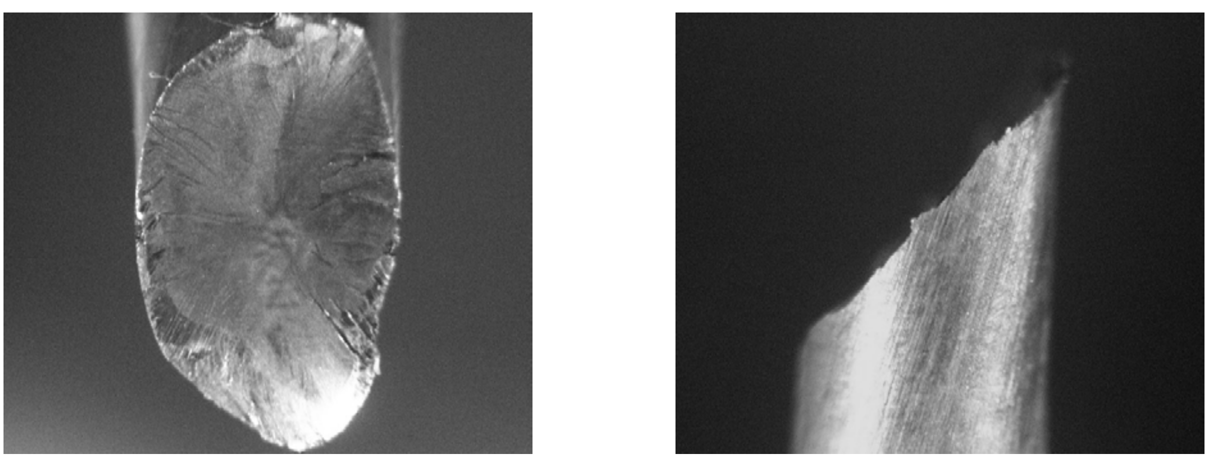

Figure 6: Fracture Surface of PWA 1484 (20 kHz).

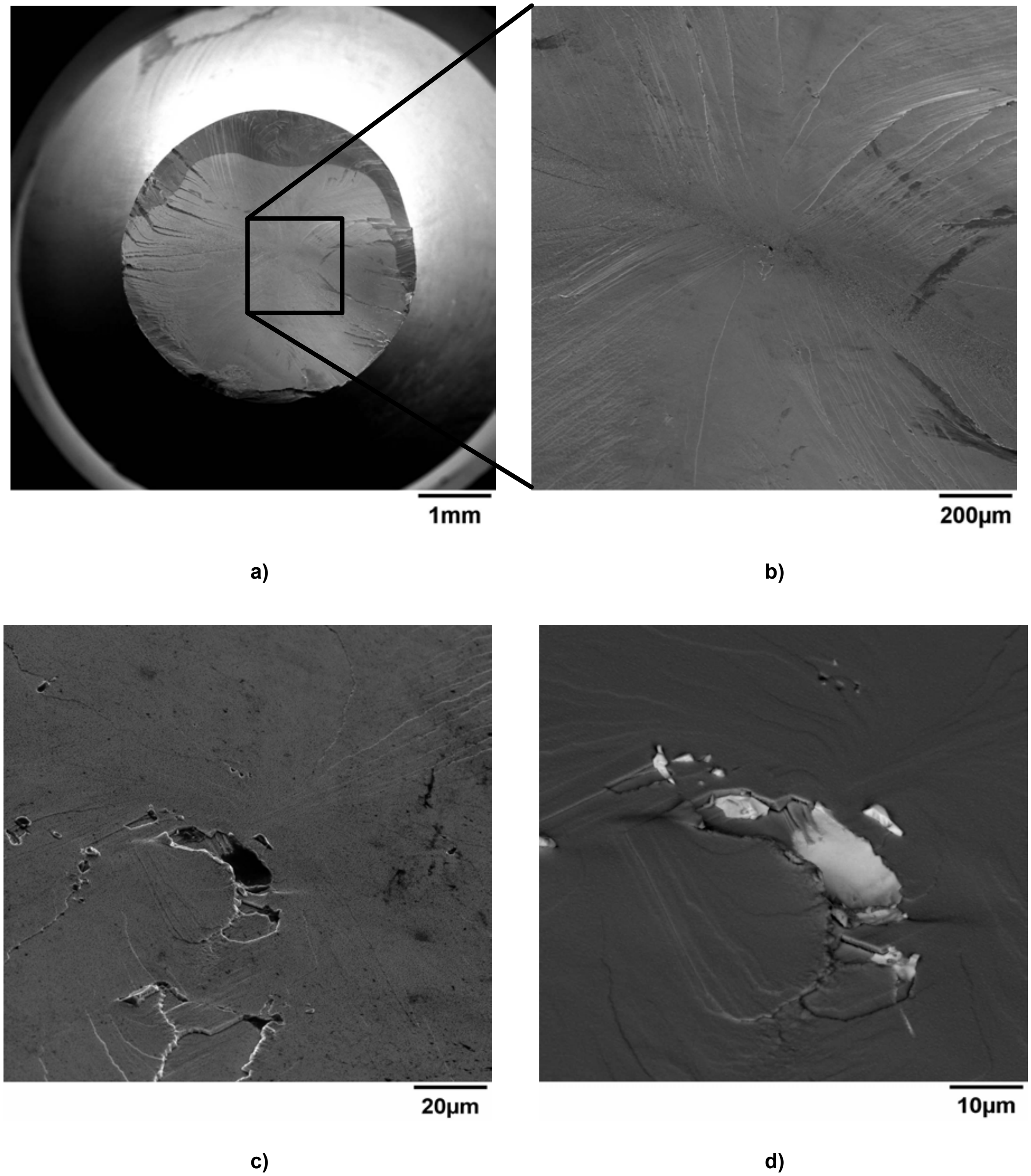

Figure 7: SEM view of PWA 1484 fracture surface: a) entire surface, b) initiation region, c) local initiation site, and d) local initiation site using backscatter imaging.

4. CONCLUSIONS

Initial results using the ultrasonic fatigue system indicate that the single crystal nickel-based superalloy PWA 1484 does not exhibit a strong frequency effect. The S-N results at 20 kHz fall slightly below the results obtained using traditional testing methods, but this may be do the limited amount of data currently available. Additional testing needs to be performed to see if these differences are statistically significant. In addition, the failure mechanisms using ultrasonic testing seem to be governed by carbides or non-metallic inclusions located throughout the material. This is in consistent with previous testing using conventional systems at lower frequencies, which showed carbide particles near the surface to be the controlling variable.

An important general conclusion of this work is that the ultrasonic fatigue system provides an efficient way of determining the mechanical behavior of materials at very high cycles, even at elevated temperatures. It allows test matrices to be completed that are impractical using conventional testing systems and provides a potential means for engine manufacturers to meet the new Air Force ENSIP guidelines. In addition, it can be used to determine potential frequency effects that may be important in engine applications where components can experience vibratory loading in the kilohertz regime.

5. REFERENCES

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SYMPOSIA DISCUSSION – PAPER NO: 32

Author's name: R. Morrissey

Discussor's name: A. von Flotow

Question: Where do you buy 600°C white paint?

Answer: From a firm which developed it for use in halogen light bulbs. The supplier details can be provided.

Discussor's name: B. Elliot

Question:

1) Can the test be done with notched specimens?
2) Would it have any impact on frequency effect?

Answer: Yes, notched specimens could be used. A group from Vienna has done some notched fatigue crack growth experiments on other materials.
The effect of notches would be material dependent and would depend on the materials frequency response during fatigue crack growth.

Discussor's name: A. Corro

Question:

1) What is the mode shape?
2) Are there no bending stress?

Answer:

1) The mode shape is axial.
2) There are no significant bending stresses when testing under fully reversed loading conditions.

Discussor's name: J. Byrne

Question: Please explain how at elevated temperature fatigue can be isolated from creep.

Answer: The ultrasonic fatigue system allows testing to 10^9 cycles in only 14 hours, which should limit creep effects. When testing at low frequency, 10^9 cycles will take months which could lead to large creep interaction.

Discussor's name: J. Calcaterra

Question: How do you measure displacement in a test with mean stress?

Answer: Rods are added to the end of the specimen and displacement is measured there.