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Fatigue crack growth behaviour of Inconel 718 with high temperature hold times

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Abstract

In this work, fatigue crack growth measurements have been made on center-cracked tension specimens of Inconel 718, where the focus has been to observe the effect of high temperature hold times on the fatigue crack growth behaviour of the material. The material testing has been done at three different temperatures, namely 450°C, 550°C and 650°C. All testing were done in an isothermal LCF context with a standard test method for measuring the fatigue crack growth rates.

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Keywords: nickel-base superalloys; fatigue crack propagation; Inconel 718

1. Introduction

In gas turbines it is important to design for as high gas temperatures as possible in order to attain a high thermal efficiency [1]. For jet engines, the increased temperature opens up for higher payloads, speed increase and a greater range. In the case of power generating gas turbines, the increase of temperature leads to lower fuel consumption, reduced pollution and thus lower costs [2]. The high-temperature load carrying ability of significant components is therefore one of the most important factors that set the limit in gas turbine design. Even though particular high temperature resistant superalloys are used, hot components are usually designed to run near their temperature and load limit. Uncertainties in models and methods used for fatigue life prediction under these circumstances are very problematic. Among the most important questions in gas turbine design is therefore how to predict the life of such components. The usual load case for these components is a start/stop thermo-mechanical load including a hold time at high temperature, where the hold time load is high enough to cause time dependent effects such as creep deformation [3]. Another complicating fact is that the mechanical properties degrade during long time exposure to high temperature by e.g. microstructural changes, oxidation and grain boundary embrittlement [4], thus reducing the

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fatigue resistance of the material. The most commonly observed micromechanisms of damage are cyclic plastic deformation, creep and oxidation. These three mechanisms are dominant during different regimes, where cyclic deformation is dominant at high frequency loading and creep and oxidation are dominant during low frequency loading [5].

This paper describes the growth of semi-elliptic surface cracks in test specimens with rectangular cross section, in Inconel 718 at temperatures 450°C, 550°C and 650°C under both cyclic and cyclic with hold time conditions.

2. Material and experimental procedure

2.1. Material data

The material used in this test series was Inconel 718. It is a wrought polycrystalline nickel based superalloy with a large amount of Fe and Cr. The composition (in weight %) of Inconel 718 is presented in Table 1. The material was delivered in the form of bars with a diameter of 25.4 mm and was subsequently solution treated and aged according to the AMS 5663 standard. The line intercept method was used to estimate the grain size to be 10 μm .

Table 1. Composition of elements for Inconel 718.

Element	Ni	Cr	Mo	Nb	Al	Ti	Fe	Co	C
Weight%	balance	17.8	2.89	5.04	0.50	0.98	18.4	0.16	0.02

2.2. Experimental procedure

Crack growth experiments were conducted on Kb-type specimens with rectangular cross sections of 4.3 x 10.2 mm, see Fig 1. An initial starter notch of nominal dimension depth 0.075 mm and total width of 0.15 mm was generated using electro discharge machining (EDM). Before the high temperature testing was carried out, the specimens were fatigue precracked at room temperature and $R=0.05$, to obtain a sharp semicircular crack with a depth of about 0.2 mm. The fatigue crack growth testing was then carried out under load control using a MTS servo hydraulic machine with a maximum load capacity of 160 kN, an Instron 8800 control system and the software WaveMaker. The furnace used was an MTS high temperature furnace with three temperature zones (model 652.01/MTS with a temperature controller of model 409.81).



Fig. 1. Instrumented Kb-type test specimen



Fig. 2. Fracture surface of the calibration specimen with visible beach marks.

The crack propagation was monitored by the direct current Potential Drop (PD) technique according to ASTM E 647 [6] using a Matelect DCM-1, 2 channel pulsed DCPD system. A direct current of 10 A was run through the specimen and the PD signal was measured by probe wires spot welded close to the notch at both sides. Additional reference probes were spot welded at the back face of the specimen, far from the notched cross-section. The crack length was derived from the ratio of the PD readings from the measuring probes to the reference PD signal to avoid problems with fluctuating currents. The PD ratio was translated to crack length through an experimentally obtained calibration function based on the initial and final crack lengths measured on the fracture surface of the test as well as by measuring induced beach marks. The beach marks were obtained by applying different load frequencies, temperatures and environments to the test specimen while performing the crack propagation testing. This gives different colored areas of the fracture surface, where the precrack, the final fracture and two crack lengths in between can be identified. The fracture surface of the calibration specimen can be seen in Fig 2.

A baseline test series was carried out with a load frequency of 0.5 Hz, see Fig 3(a). As mentioned previously, the tests were conducted at three different temperatures, 450°C, 550°C and 650°C. Two tests were done at each temperature. Furthermore hold time tests were carried out using a trapezoidal waveform with 1 s ramp up, hold at maximum load and 1 s ramp down, see Fig 3(b). The hold time tests were done at the temperatures 550°C and 650°C for the hold time lengths of 90 s and 2160 s. One test was done for each case, except for the 550°C and 90 s hold time test, where two tests were done. All tests were done in laboratory air and at load ratio of $R=0.05$. A summary of the tests is shown in Table 2.

One sample for each test case was analyzed using an analytical scanning electron microscope (SEM), Hitachi SU70 operating at 20 kV. The preparation was done by first making an axial cut in a diamond tip cutter, and then by grinding and mechanical polishing of the surface. No etching was performed on the samples and contrast was achieved from differences in composition and crystallographic orientation only.

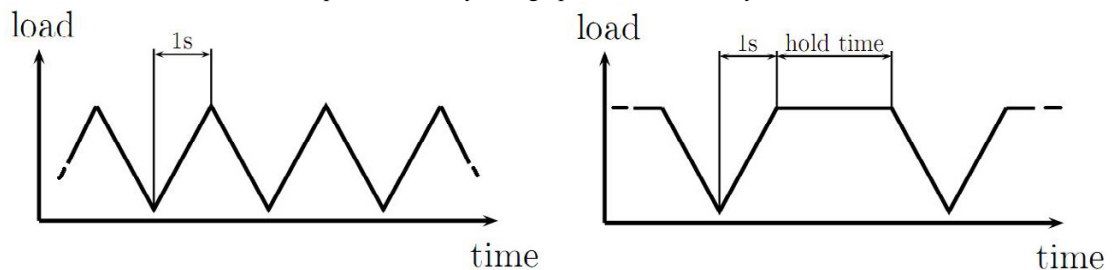


Fig. 3. Load-time profiles for (a) baseline tests and (b) hold time tests.

Table 2. Summary of tests

Temperature	Baseline 0.5 Hz	90 s Hold time	2160 s Hold time
450°C	2	-	-
550°C	2	2	1
650°C	2	1	1

2.3. Evaluation procedure

As has already been stated, the PD technique has been used to monitor the growth of the cracks. This technique provides crack size by measuring the potential drop caused by the increase of crack area. Since the technique does not depend on visual accessibility, it is well suited for special cases like vacuum or high temperature environments. To evaluate the crack size from the measured PD values, the following procedure has been adopted.

Firstly, in order to reduce the problems associated with thermo-electrical effects, lack of stability in supplying current and changes in the instrumentation or changes of temperature, a normalized value of the PD is obtained by dividing the measured PD value with the reference value [6].

Generally, crack length is correlated to the normalized PD values through an experimentally obtained function (calibration curve). Since the PD technique has an accuracy of 0,01 mm crack length, the obtained crack lengths have to be rounded off. This process gives the same crack length for several successive cycles, and one thus has to select the unique (identical) crack sizes and calculate the corresponding number of cycles through a mean method [6].

The solution for the stress intensity factor K was analytically obtained using a presolved case for a semi-elliptic surface crack [7]. From this the ΔK values were calculated. The crack growth rate per cycle da/dN was then calculated using a MATLAB code. For the hold time tests, PD values were recorded each 2s during the test procedure. Using a filtering process, one datum point was obtained for each loading cycle. In this paper only one experiment is presented for each identical test case.

In order to model the experimental behaviour (setting up trendlines) the common Paris Law was adopted

$$da/dN = C \Delta K^m \quad (1)$$

Parameters were evaluated for each test case, using a least square technique.

3. Results

3.1. Crack growth

The baseline crack growth data (da/dN vs ΔK) are found in Fig 4(a). As can be seen the growth rate increases with increasing temperature. The room temperature precrack of a test specimen were examined in a microscope using the previously described method, see Fig 4(b). As can be seen, the fracture mode for the precrack was primarily trans-granular. Furthermore one test specimen of each temperature of the baseline test was examined, and showed also a primarily trans-granular fracture mode. The crack appearance for the 650°C case is shown in Fig 5.

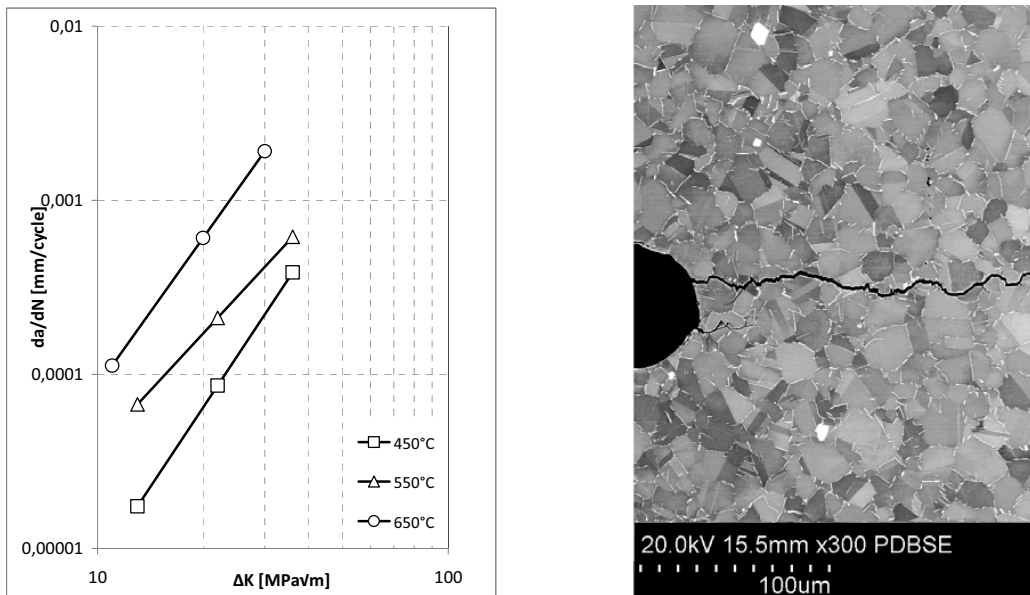


Fig. 4. (a) Trendlines for Baseline testing, (b) Precrack

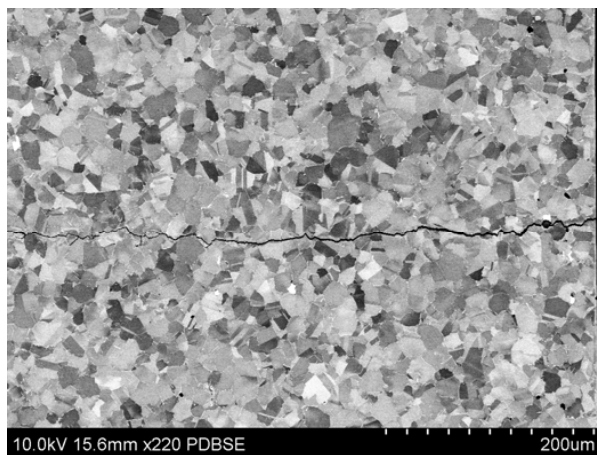


Fig. 5. Baseline crack at 650°C

When a hold time of 90 s is applied, the crack growth rate increased dramatically, as can be seen in Fig 6(a) (cf. Fig 4(a)). Specimens tested at 550°C and 650°C, respectively, were examined in microscope using the previously described method. A change of fracture mode could be seen for both temperatures, when the 90 s hold time was applied. The crack of the 650°C 90 s hold time test specimen can be seen Fig 6(b). As can be seen, the fracture mode is mainly intergranular.

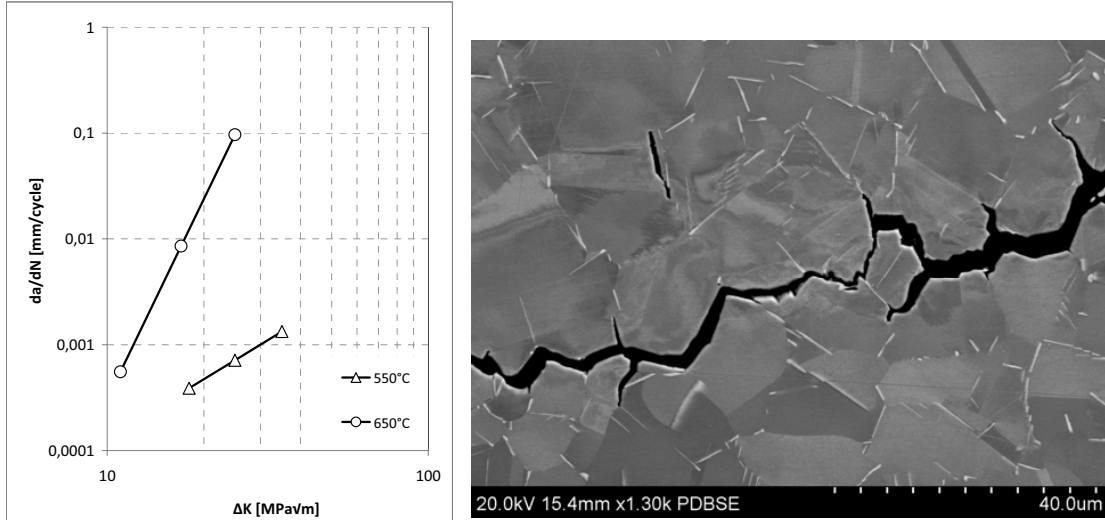


Fig. 6. (a) Trendlines for 90 s hold time tests, (b) 650°C crack at 90 s hold time

When a hold time of 2160 s is applied, the crack growth rate is further increased, as can be seen in Fig 7(a) (cf. Fig 6(a)). Once again two test specimens, tested at 550°C and 650°C, respectively, were examined in microscope. The crack of the 650°C 2160 s hold time test specimen can be seen in Fig 7(b). The fracture mode is mainly intergranular.

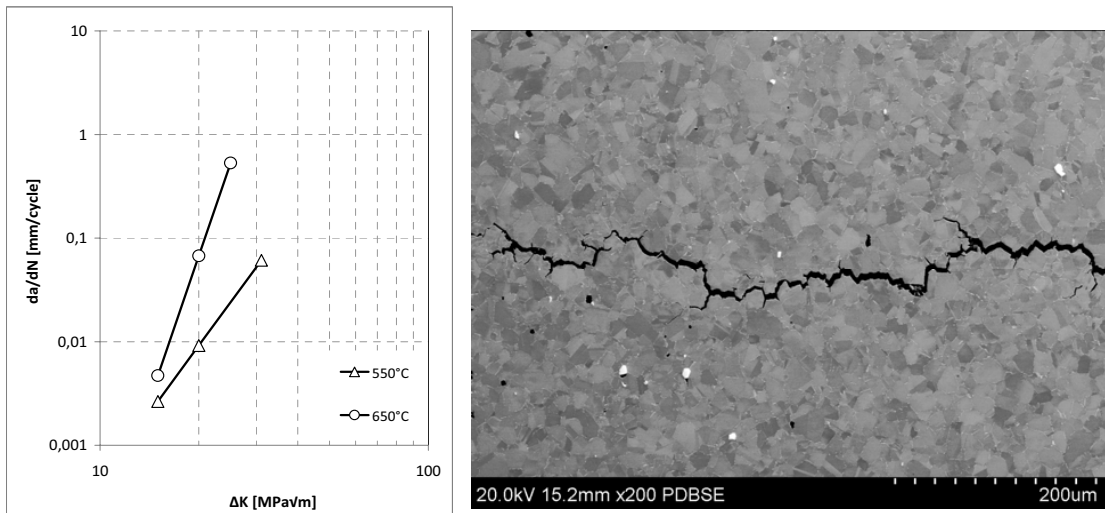


Fig. 7. (a) Trendlines for 2160 s hold time tests, (b) 650°C crack at 2160 s hold time

The evaluated parameters for the Paris law equation are presented in Table 3, below.

Table 3. Evaluated parameters for the Paris law equation

Temperature	C	m
Baseline 0.5 Hz		
450°C	$7,228 \cdot 10^{-9}$	3,074
550°C	$2,531 \cdot 10^{-7}$	2,766
650°C	$1,286 \cdot 10^{-7}$	2,825
90 s Hold time		
550°C	$1,813 \cdot 10^{-6}$	1,856
650°C	$1,588 \cdot 10^{-10}$	6,283
2160 s Hold time		
550°C	$2,188 \cdot 10^{-8}$	4,322
650°C	$6,191 \cdot 10^{-14}$	9,252

4. Discussion

The experiments show two different regimes of active fracture mode. In the baseline testing it was shown that for all temperatures the active fracture mode was transgranular cracking. As can be seen in Fig 8, there are a lot of plastic deformation (slip bands) around the crack path, indicating that the dominating fracture mechanism in the baseline tests is cyclic plastic deformation around the crack tip.



Fig. 8. Slip bands around the crack path of Baseline test at 650°C

The other fracture mode present in the testing can be seen when a hold time is applied. At both 90 s and 2160 s hold times and at both 550°C and 650°C the fracture mode is mainly intergranular. As can be seen in Fig 6(b), very few slip bands can be observed around the crack path for the hold time tests. This indicates that another fracture

mechanism is dominant during these tests. The crack growth rate (da/dN) is also vastly increased when a hold time is applied. For 550°C the increase of crack growth rate from zero to 90 s hold time is, at a certain ΔK level approximately 3 times, and for 2160 s it is approximately 50 times. For 650°C there is a much greater increase; from zero to 90 s hold time we find approximately 50, and for 2160 s we get more than a 100 times higher crack growth rate. For comparison, the increase in crack growth rate from zero hold time at 450°C to 2160 s hold time at 650°C, an increase of approximately 1000 times is found, cf. Fig 9, where the trendlines for all test cases are presented. The increase in crack growth rate along with the active fracture mode indicates that a time dependent fracture mechanism is active. In the literature, there seems to be a consensus, that this intergranular crack growth is due to oxygen.

The underlying mechanism of the interaction between oxygen and the crack tip is still not clear, but there are two dominating theories: stress accelerated grain boundary oxidation (SAGBO) and dynamic embrittlement (DE) [8]. The SAGBO process involves oxidation of grain boundaries ahead of the crack tip and subsequent cracking of the oxide, exposing new surfaces to the oxygen. The DE theory on the other hand advocates embrittlement of the grain boundary by diffusing oxygen, separation of the embrittled boundaries and subsequent oxidation of the fresh surfaces. DE requires oxygen diffusion over very short distances, which has been shown to be consistent with the rapid halting of a crack growing under sustained load when the oxygen pressure is removed [9]. An extensive literature review [8] of gas phase embrittlement (a general term describing the embrittling effects of gaseous species) favors DE as the mechanism behind enhanced sustained load crack growth in superalloys, but the details of the environmental interactions during cyclic loading may well be more complicated. Studies by Andrieu et al. [10] and Molins et al. [11] have indicated that the short range interaction kinetics may be controlled by oxide formation at the crack tip, where the growing oxide may permit or deny oxygen penetration (formation of NiO with associated vacancy formation to aid penetration and transport of oxygen, and formation of passive Chromium oxides depending on oxygen pressure and temperature). With increasing time, the oxide will grow thicker and reduce the effective oxygen partial pressure at the crack tip, but the cyclic loading will repeatedly (depending on waveform) break up the oxide, leaving the crack open to further oxygen attack. In addition to the purely chemical factors, the often complex interactions between stress state and creep relaxation at the crack tip, alloy chemistry, oxide formation and load reversal effects during cyclic loading will also affect the crack propagation process [2].

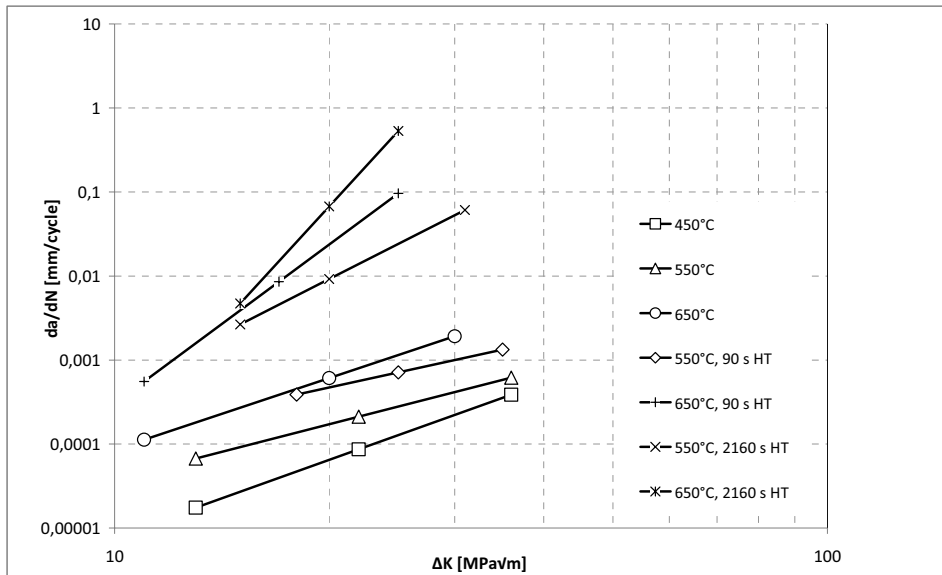


Fig. 9. Trendlines for all tests

To investigate how much the grain boundaries have been weakened, a comparison of the amount of crack length found in each unloading and reloading are done for the baseline tests and the hold time tests. To evaluate the unsmoothed and unfiltered crack lengths in the hold time tests, a method has been set up to reduce the scatter within each loading cycle. In this method the loading cycle is divided into five regions, where the crack length values within each region is evaluated using an average method. The chosen regions are presented as points, and can be seen in Fig 10. These points can then be compared with corresponding values for other temperatures and hold times.



Fig. 10. Crack length vs time for baseline test done at 550°C

Crack lengths over one loading cycle at 550°C for approximately the same crack length are plotted for the three test cases in Fig 11. As can be seen, the increase in crack length for each unloading and reloading are much larger for the hold time tests then for the baseline test. Furthermore, longer hold time will also give a much larger crack growth during unloading and reloading than the test with shorter hold time. This is due to the time dependent grain boundary weakening effect, as discussed above. The amount of crack growth during the hold time can also be seen.

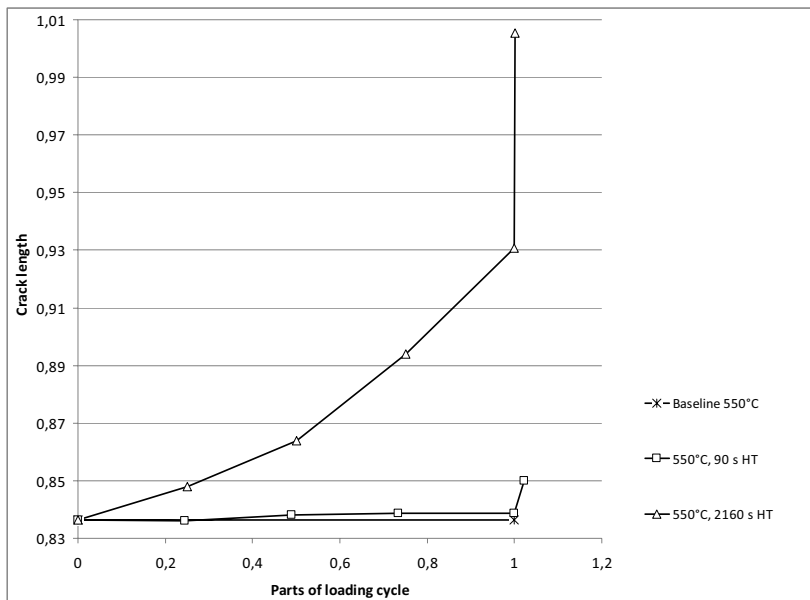


Fig. 11. Crack length over one sequence for all three test variants at 550°C

5. Summary and conclusions

High temperature fatigue crack growth in Inconel 718 has been studied for several different temperatures. The tests were conducted both without hold times and with hold times of different lengths. The main conclusions are:

- The crack growth rate increases with increasing temperature and with increasing length of the hold times.
- There is a change in fracture mode from transgranular to intergranular cracking when a hold time is applied.
- When the crack growth during the hold time is separated from the crack growth occurring during the unloading and reloading, one can see that significant embrittlement of the grain boundaries must have occurred. This leads to a significant increase in crack growth during one load reversal compared to the baseline tests without any hold time.

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