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Time- and cycle-dependent crack propagation in Haynes 282

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ABSTRACT

Haynes 282 is a promising superalloy candidate for several high-temperature applications in both aero and land-based gas turbine engines. To study the crack growth behaviour under time-dependent conditions relevant to such applications, a test program was carried out at room temperature up to 700 °C with conditions ranging from pure cyclic to sustained tensile loading. At 650 °C and high stress intensity factors the crack growth was fully time-dependent for dwell-times of 90 s and longer. At lower stress intensities, the behaviour was mainly controlled by the cyclic loading, even under dwell conditions. The behaviour under dwell-fatigue conditions was well described by a liner superposition model. The main crack growth occurred transgranularly at room temperature and there was a transition in cracking behaviour from cycle dependent transgranular growth to time-dependent intergranular propagation at ~45 MPa $\sqrt{m}$ for the high temperature tests. No effect of cyclic frequency could be observed at room temperature, and at lower frequencies the crack growth rate increased with temperature.

1. Introduction

Haynes 282 is a newly developed γ' (Ni_3(Al, Ti)-$L1_2$) strengthened Ni-base superalloy, exhibiting good creep strength, thermal stability, weldability, and fabricability, compared to e.g. Waspaloy [1]. It is a candidate for several high-temperature applications in both aero- and land-based gas turbine engines, as well as steam turbines, ultra super critical power plants, and automotive applications.

In such components, combinations of high temperatures (~550–800 °C) and sustained periods of high tensile loads can lead to accelerated crack growth rates. Under these conditions, the influence of an oxidising environment has long been recognised and the accelerated crack growth rate is often accompanied by a change in crack growth mechanism from transgranular to intergranular crack paths. This is especially true for fine grained and high strength alloys [2–5]. For lower strength alloys, the effects of creep deformation on crack growth should be considered carefully since stress relaxation ahead of the crack tip lead to blunting which will lower the mechanical driving forces [6–8]. A similar retardation effect has also been observed when an overload is applied prior to the dwell-time [9].

At this point in time, detailed information regarding the high-temperature properties of Haynes 282, and in particular the fatigue, dwell-fatigue and sustained load crack growth resistance, is very limited. The effect of temperature and loading frequency has been investigated in [10–13] but to the author's best knowledge, no studies on the effect of dwell-times on the fatigue crack propagation in Haynes 282 are available.

In the study by Buckson and Ojo [10], the fatigue crack growth behaviour of Haynes 282 at room temperature and at 600 °C, was studied using the stress ratios $R=0.1$ and $R=0.7$ and the frequencies 0.05 Hz and 15 Hz. They concluded that an increase in load ratio increased the fatigue crack growth rates, as expected. They also reported that the fatigue crack growth rate would be influenced by frequency at room temperature, and that there would be an inverse effect of temperature at low test frequencies, which is somewhat contradictory to common assumptions.

In [11–13] by Rozman et al. the fatigue mechanisms of Haynes 282 at high temperatures are characterised, by evaluating the fatigue crack growth rates at three different temperatures, 550 °C, 650 °C, and 750 °C and two loading frequencies, 0.25 Hz and 25 Hz. It was found that the effect of frequency on the fatigue crack growth rates was minor at 550 °C but much more significant at 650 °C and 750 °C. For the temperatures investigated the effect of decreasing the loading frequency was an increase in fatigue crack growth rate. The crack path was observed to be transgranular for the temperatures and frequencies used. Except at 750 °C, where there were indications of limited intergranular cracking excursions at both loading frequencies [12].

The present study is partly motivated by the somewhat controversial results regarding the effects that temperature and

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frequency have on the fatigue crack growth behaviour reported by Buckson and Ojo in [10]. But also due to the complete lack of studies on dwell-fatigue crack growth in Haynes 282. Rozman et al. [12] pointed out that although the behaviour of Haynes 282 could be considered as robust and predictable within the tested temperature and frequency range, there is a great risk associated with the introduction of dwell-times and sustained loads, which has not been studied so far. For this reason, a test program was carried out to characterise the fatigue, dwell-fatigue and sustained load crack growth resistance of Haynes 282 at room temperature, 650, and 700 °C. Detailed metallographic investigations of the tested samples were performed to determine the crack growth mechanisms.

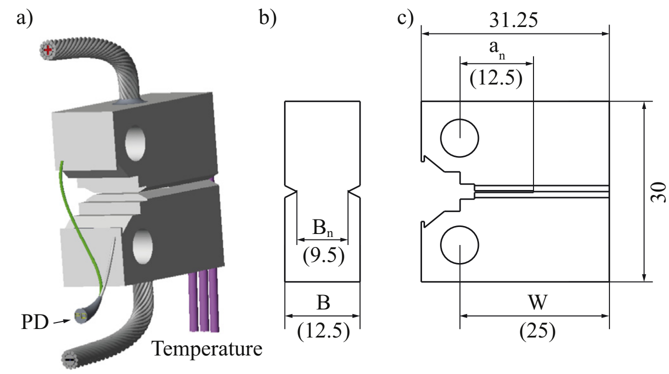

Fig. 1. A 3D view and specimen drawing of an instrumented CT specimen with side grooves. All measurements are in mm.

2. Experimental procedure

The material used in this study was Haynes 282 delivered in the form of a forged ring, heat-treated accordingly: solution heat treated for 2 h at 1100 °C then aged for 2 h at 1010 °C, with a final aging treatment at 788 °C for 8 h. The material had a chemical composition as shown in Table 1 and an average grain size of 120 µm or #3 according to E112.

All tests were performed according to E647 using the compliance method for crack length measurements at ambient temperature while the potential drop (PD) technique was used at elevated temperatures (650 °C and 700 °C). The specimen and PD-instrumentation is illustrated in Fig. 1(a). Testing was done using compact tension (CT) specimens measuring: width W=25 mm, Fig. 1(c), and a full thickness B=12.5 mm, Fig. 1(b) however, side-grooves were used for all tests giving a net section thickness of B_n = 9.5 mm, Fig. 1(b). The specimens had an electro-discharge machined starter notch measuring a_n=12.5 mm, Fig. 1(c), and were fatigue pre-cracked at room temperature to a crack length of a_0 = 16 mm using a frequency of 10 Hz, a load range of $\Delta P = P_{max} - P_{min}$ = 2500 N, and a load ratio of $R = P_{min}/P_{max}$ = 0.1.

Room temperature fatigue crack propagation tests were performed using different stress ratios (R=0.1, and R=0.5) and different frequencies (f=0.05 Hz, 1 Hz, and 15 Hz). In all tests a load range of 2.5 kN were used. The crack opening displacement was measured using an Instron clip gauge extensometer and the crack growth rates were evaluated according to E647. Table 2 summarises all the parameters used for the tests that run at room temperature.

High temperature crack propagation tests were conducted at 650 °C with different dwell-times (90 s and 2160 s), as well as under sustained load conditions, with a constant ramp up/ramp down rate yielding 10 s single ramp time each for loading and unloading. At 700 °C only sustained load tests were performed. Testing was done using a 100 kN Zwick servo electric tensile testing machine (Kappa 50DS), equipped with a three zone (high temperature) furnace. Table 3 summarises all the parameters used for the tests that run at elevated temperature. All tests were performed according to E647 using a 20 A pulsed direct current potential drop (DCPD) system where crack lengths were obtained by

Table 2
Summary of ambient temperature fatigue crack growth tests.

Frequency (Hz)	R-ratio	Load range ΔP (N)
15	0.1	2500
1	0.1	2500
0.05	0.1	2500
15	0.5	2500

Table 3
Summary of elevated temperature crack growth tests.

Temperature (°C)	Loading condition	Load (N)	R-ratio
650	90 s dwell-time	ΔP = 3500	0.05
650	2160 s dwell-time	ΔP = 3500	0.05
650	Sustained load	P=5000	–
700	Sustained load	P=4500	–
700	Sustained load	P=5000	–

using the Johnson formula, according to

$$a = \frac{2W}{\pi}\cos^{-1}\frac{\cosh\left(\frac{\pi y}{2W}\right)}{\cosh\left[\frac{U}{U_0}\cosh^{-1}\left(\frac{\cosh\frac{\pi y}{2W}}{\cos\frac{\pi a_0}{2W}}\right)\right]}, \tag{1}$$

where U_0 and a_0 are the initial values of the potential and the crack length, respectively, while U and a are the actual values of the potential and the crack length, y is one half of the gauge span for U and W is the sample width. The analytical solution of the stress intensity factor, K, for CT-specimens with side grooves was obtained from E399, according to

$$K = \frac{P}{\sqrt{B \cdot b_n \cdot W}} f\left(\frac{a}{W}\right) \tag{2}$$

where

Table 1
Composition of elements for Haynes 282 in wt%.

Alloy	Ni	Cr	Co	Mo	Ti	Al	Fe	Nb	C	Si	Mn	Cu	Ta	W	B
Haynes 282	56.875	19.57	10.33	8.71	2.24	1.48	0.50	0.10	0.063	0.05	0.04	0.01	0.01	0.01	0.005