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Effect of notches on creep–fatigue behavior of a P/M nickel-based superalloy

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ABSTRACT

A study was performed to determine and model the effect of high temperature dwells on notch low cycle fatigue (NLCF) and notch stress rupture behavior of a fine grain LSHR powder metallurgy (P/M) nickel-based superalloy. It was shown that a 90 second (s) dwell applied at the minimum stress ("min dwell") was considerably more detrimental to the NLCF lives than similar dwell applied at the maximum stress ("max dwell"). The short min dwell NLCF lives were shown to be caused by growth of small oxide blisters which caused preferential cracking when coupled with high concentrated notch root stresses. The cyclic max dwell notch tests failed mostly by creep accumulation, not by fatigue, with the crack origin shifting internally to a substantial distance away from the notch root. The classical von Mises plastic flow model was unable to match the experimental results while the hydrostatic stress profile generated using the Drucker–Prager plasticity flow model was consistent with the experimental findings. The max dwell NLCF and notch stress rupture tests exhibited substantial creep notch strengthening. The triaxial Bridgman effective stress parameter was able to account, with some limitations, for the notch strengthening by collapsing the notch and uniform gage geometry test data into a singular grouping.

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1. Introduction

A new generation of powder metallurgy (P/M) disk superalloys has been designed for higher engine operating temperatures by improvement of their strength and creep resistance. This increase in the engine operating temperatures has resulted in additional emphasis being placed on high temperature environmental resistance and dwell behavior of these alloys to determine their long term high temperature durability. The increased strength and creep resistance of these alloys may also increase their notch sensitivity to fatigue loading and thus have a profound effect on the notch low cycle fatigue life. NLCF is a key mechanical property of the highly stressed gas turbine rotating components since it simulates behavior at notches and bolt holes which are the regions from where the majority of failures of rotating components tend to originate [1].

With the increase in the disk operating temperatures, sustained dwells applied at the maximum stress have been shown to significantly degrade both smooth and notch LCF fatigue life [2–4]. More surprising has been a finding by Bache et al. [5] that an imposition of a 90 s dwell at the minimum stress produced an even greater reduction in NLCF life. This was also confirmed in our study of the ME3 disk alloy [6]. The differences in the notch fatigue life response to max dwell and min dwells are thought to be influenced by both notch stress relaxation and environmental degradation [5,6], but more work remains to be performed to further understand the mechanisms by which these interactions occur.

The presence of notches adds another level of complexity to the already complex world of environment-load history interactions. The resulting multi-axial stress state at the notch root, combined with visco-plastic high temperature material response, can produce significant redistributions of stresses and strains in the notch region which in turn affect the life and the overall durability of the disk alloys. The role that axial stress, hydrostatic stress and the effective stress play in determining the durability needs to be sorted out. Due to these complexities, currently available life prediction models are not able to accurately predict dwell notch low cycle fatigue life. Formulation of more accurate life prediction models requires an improved understanding of the damage mechanisms responsible for material degradation and accumulation of fatigue damage. The key to gaining this understanding is the identification of the active material damage mechanisms for a given set of test conditions and their relationship to the redistribution of the notch root stresses and strains which takes place during the prolonged dwells.

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The approach of the current study was to isolate as much as possible the major variables which affect the dwell NLCF behavior so that their individual mechanistic contributions to material durability could be studied, quantified and modeled. The work was performed by testing the NASA developed Low Solvus High Refractory (LSHR) P/M disk alloy. A variety of test types were conducted to characterize the material behavior. Cyclic, cyclic-dwells, stress-rupture and creep testing was performed using both notch and uniform section specimen geometries to characterize material response under varied loading conditions. Baseline cyclic tests were performed as well as notch dwell fatigue tests with 90 s holds at either maximum or minimum stress. The application of 90 s dwells at the minimum stress was utilized so that the role of the environment can be studied without the complication of visco-plastic stress redistribution. Notch and smooth stress-rupture testing was used to quantify the creep contribution to the damage process. While most of the testing was performed in lab air, selected specimens were tested in vacuum to isolate and quantify the environmental contribution to the damage evolution.

This paper compares the pronounced effect that both environmental damage and the visco-plastic stress redistribution have on the lives of LSHR specimens. The aim of the study is to identify the key parameters which account for these differences in behavior and to present a methodology which can explain and predict these results.

2. Materials and procedure

The LSHR P/M alloy with a composition consisting in weight percent of 20.7 Co, 4.3 W, 3.5 Al, 3.5 Ti, 2.7 Mo, 1.6 Ta, 1.5 Nb, 0.05 Zr, 0.03C, 0.03 B with balance Ni was used in the study. Small pancake forgings approximately 150 mm in diameter and 37 mm thick of this composition were heat treated as follows to produce a fine grain subsolvus microstructure: solution at 1135 °C, fan cooled and aged at 855 °C/4 h + 775 °C/8 h. The heat treatment produced a fine grain microstructure approximately 5–10 μm in diameter (ASTM 11-12) with the microstructure shown in Fig. 1. The typical tensile test properties and the associated stress–strain curve are shown respectively in Table 1 and Fig. 2. The stress–strain curve can be modeled by a bi-linear fit with the elastic modulus at the test temperature of 183.6 GPa and the linear hardening modulus of 16.15 GPa (Fig. 2). Specimens were machined from heat treated forgings. Approximate cooling rate from the solutioning temperature was designated for the location of each blank removed from the pancake forgings.

All testing was performed at 704 °C and consisted of cyclic notch fatigue, cyclic notch dwell fatigue, creep notch rupture, combo-bar creep and uniform gage creep tests. The geometry of the notch LCF specimen is shown in Fig. 3. All the notch specimen geometries used in the program had an elastic stress concentration factor (K_t) of 2.0. Combo-bar geometry, consists of a uniform gage section and a notch region with the notch diameter being equal to that of the smooth section. The details of all the test conditions are shown for the cyclic and cyclic dwell NLCF tests in Table 2 and for the creep and stress rupture tests in Table 3. Three different waveforms were utilized: sinusoidal with frequencies of 10 Hz and 0.333 Hz, max dwell (1.5–90–1.5) seconds and min dwell (1.5–1.5–90) seconds with dwell cycles shown in Fig. 4. As shown in Tables 2 and 3, in addition to lab air, selected tests were performed in vacuum. The testing was conducted at various net section stresses ranging from 483 MPa to 896 MPa with the majority of the tests being conducted at 793 MPa to determine the data repeatability.

Stress relaxation testing was conducted at 704 °C to obtain a constitutive creep relationship for the alloy for use in the visco-plastic modeling. Stress relaxation was measured after a 1% total strain was achieved in a standard tensile test. The specimen was then held at 1% strain for 100 h while the change in stress was monitored by an automated data acquisition system. Visco-plastic

Table 1
Tensile properties of subsolvus LSHR at 704 °C.

Yield strength (MPa)	UTS (MPa)	Elongation (%)	RA (%)
1110	1282	9.5	15

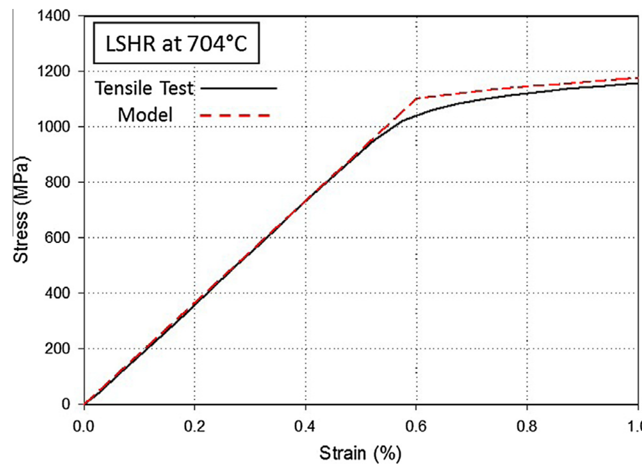
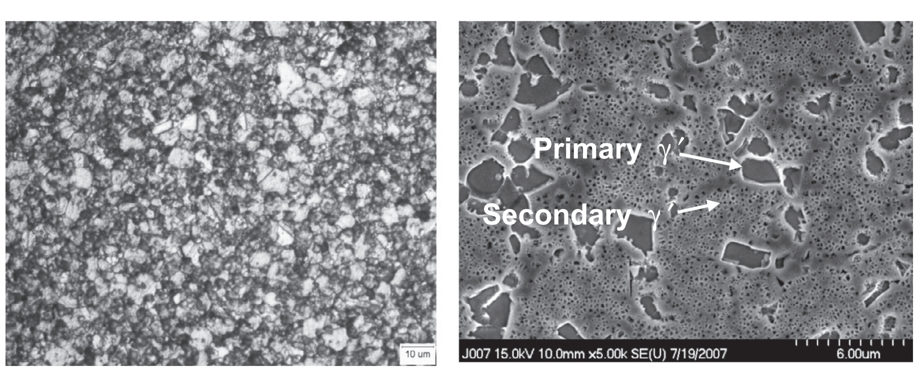


Fig. 2. Tensile test and the bi-linear fit model for subsolvus LSHR at 704 °C.



(a) typical grain structure (b) primary and secondary γ′ precipitates

Fig. 1. Subsolvus LSHR grain structure and the strengthening γ' precipitate characteristics.