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Thermomechanical fatigue crack growth from laser drilled holes in single crystal nickel based superalloy

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ABSTRACT

The test results undergoing thermomechanical fatigue of single crystal PWA1484 crack growth showed that the life of TMF specimens with notches (in this case laser drilled holes) is 4 times shorter than the number of cycles to failure observed on smooth gage section specimens (without holes) under the same loading conditions. Such a significant change in number of cycles to failure must be accounted in any damage tolerant turbine airfoil design system. The detailed fractographic analysis demonstrated that all cracks start crystallographically along the {1 1 1} octahedral crystallographic planes and later change to mixed mode fracture. Most of the crack propagation takes place at the low temperature portion of the cycle in the out-of-phase test; however there is noticeable damage accumulation during the high temperature compressive load portion of the cycle. Crack propagation under TMF loading conditions is considerably faster than corresponding isothermal LCF crack growth tested at the temperature and similar loading conditions of the tensile part of the TMF cycle. As results show, the applicability of the LEFM methods for single crystal TMF crack growth prediction is limited and at least should consist of mixed mode crack analysis.

A new method for detecting cracks during a TMF test using induction thermography was employed. This method, coined the Active Inferred Crack Detection System (AICD), demonstrated high effectiveness in following crack progression under cyclic loading making it well suited to perform TMF crack growth testing. Using this experimental technique we also investigated the effect of secondary crystallographic orientation on crack propagation.

1. Introduction

This paper points out the significance of including damage tolerant design philosophies to turbine airfoils that incorporated cooling holes in them. Turbines in aircraft turbojet engines are being subject to increasingly higher temperatures to improve fuel efficiency. High turbine efficiency requires the ability of turbine blades to withstand gas temperatures of the order of 1350–1550° degrees centigrade. In polycrystalline materials these increased temperatures would cause creep strains along grain boundaries that would be unacceptable. Turbine blades must maintain adequate strength throughout long service intervals for commercial engines and throughout many complex mission types for military engines. Even single crystal materials though must be pushed to their limits to insure that engine performance is maximized. Airfoils in modern gas turbine aircraft use a systems approach for cooling to achieve required component life. There are three basic components to these systems: (i) a cast nickel single crystal super alloy in combination with, (ii) thermal barrier coatings and finally (iii) a sophisticated cooling scheme consisting of intricately designed channels and holes through the core and surface of the airfoil.

A typical modern single crystal superalloy has an ordered $L1_2$ structure, with a matrix based on a γ face-centered cubic structure and regular cubes of γ' phase, based on the intermetallic compound Ni_3Al, which occupy from 65% to 70% of the volume [1]. The composition of these superalloys has evolved parallel with advancements in casting processes. Single crystal alloys are precipitation-strengthened, cast superalloys based on the Nickel–Chromium–Aluminum (Ni–Cr–Al) system [2]. The macrostructure is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. A typical microstructure of the second generation Ni-base superalloy is shown in Fig. 1 with the typical γ' cuboid size of 0.45 μm.

The excellent high-temperature creep and fatigue resistance of these superalloys is a result of a combination of solid-solution strengthening, absence of deleterious grain boundaries, and a high volume fraction of precipitates that act as barriers to dislocation

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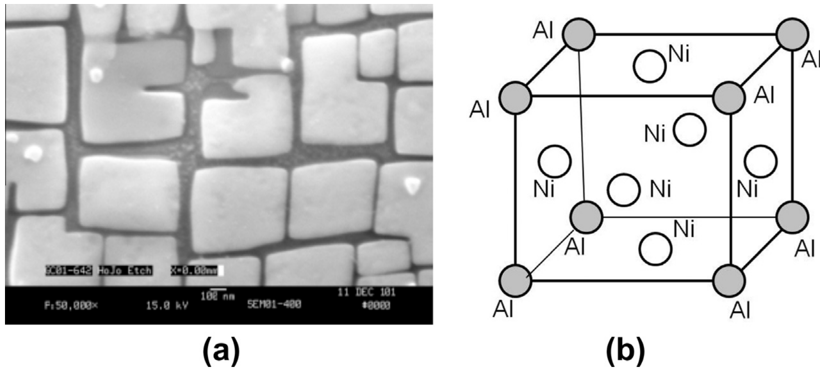

Fig. 1. (a) Typical microstructure of Ni-based superalloy single crystal PWA 1484. (b) Scheme of crystallographic cell of $L1_2$ structure.

motion [3]. However, fatigue crack initiation also depends on the microscopic defects, which can be categorized as intrinsic defects and deviant material defects.

Single superalloy crystals deform at high temperature by shearing along twelve octahedral $\{111\}\langle 110\rangle$ and six cube $\{001\}\langle 110\rangle$ slip systems, that are observed only at high temperature. Thermal mechanical fatigue (TMF) cracking usually takes place when inelastic deformation and corresponding energy dissipation is suppressed at low temperatures while creep and oxidation occur at high temperatures and generate stress redistribution affecting low temperature state. Recently, MacLachlan and Knowles [4], Staroselsky and Cassenti [5,6] used slip system models and structural elasto–viscoplastic calculation procedures for analysis of turbine components. Critical locations in turbine airfoils are subject to the combined influences of thermally driven strain transients and creep damage resulting from stresses during operation [7]. TMF cracking occurs at many locations on turbine airfoils, including pressure and suction sides and both leading and trailing edges [8,9]. In single crystal blades, cracks are observed both parallel and normal to the casting growth direction. The phasing between thermal and mechanical loads defines the TMF response of the airfoil [7–11]. The extremes of load-temperature phasing are in-phase (IP) and out-of-phase (OP). In-phase cycles occur when an unconstrained local area of the blade is mechanically loaded at the same time the temperature increases. Out-of-phase cycling occurs when a locally constrained area of the blade tries to expand as temperature increases, which usually causes the local compression with the rise of temperature. OP cycling is generally the most harmful because stress relaxation at the maximum temperature develops high mean stresses.

Hot section components in advanced gas turbine engines experience severe cyclic temperature gradients and mechanical loads, particularly during takeoff and landing operations. As a consequence, TMF is a major life-limiting factor for cooled gas turbine blades. TMF cracks are nucleated at the blade cooling hole locations due to a combination of high mechanical and thermal cyclic stresses and strains [9,12]. The synergy between fatigue damage and time-dependent phenomena, such as creep and oxidation, can be much stronger under thermal transient conditions than under isothermal loading conditions [13,14]. Therefore, TMF testing is extremely important in order to simulate the deformation and cracking behavior of blades at performance-critical locations [12–17].

While actual turbine blade TMF cycles are a combination of IP and OP cycles, two basic types of TMF cycles are commonly employed in laboratories: IP cycle, where the mechanical strain is the highest at the maximum temperature, and OP cycle, where the mechanical strain is the highest at the minimum temperature. It is, of course, possible to use any arbitrary phase angle between the specimen temperature and mechanical strain. While temperature varies periodically with time, special care is exercised to minimize the temperature gradient across the specimen section. This requirement for spatial uniformity in dynamic temperature distribution within the gage section necessitates relatively long cycle times. TMF testing requires careful monitoring, control, and measurement of a large number of experimental variables.

The test data obtained from TMF specimens is traditionally used for low cycle fatigue (LCF) cycles to crack initiation design purposes. As a result, only safe life design approaches might be employed. However, for the damage tolerant assessment, it is essential, if not critical that TMF crack initiation, location, propagation path, and growth rate information are measured as well. The development of methodology for a TMF damage-tolerant approach based on fracture mechanics is needed in order to reveal these specific physical damage phenomena. In addition, any fracture mechanics TMF modeling requires test data on TMF crack growth mechanisms and kinetics.

As have been already noted, most TMF cracks in airfoils start from the cooling holes. Thus, a new thermomechanical fatigue experimental technique is needed to measure the structural life of the specimen containing through holes similar to the ones that are drilled in a cooled airfoils. In this paper we describe our basic TMF test procedure on specimens with laser drilled holes. We investigate the cooling hole effect on fatigue crack growth and on corresponding TMF life compared to base line cast nickel single crystal data. The developed method would allow explicit measurements of the effects of crystal secondary orientation, hole geometry, skew angles, and laser drilling effects, etc. on TMF crack initiation and propagation. Comparison of smooth specimen data with results obtained on the specimens with small holes allows assessment of the TMF endurance and component structural life of the notched structures as well as evaluation of the role that local stress concentration around small features produce. Thus, these TMF test results can be directly used to evaluate structural life of the cooled airfoils as well as provide necessary information on the applicability of smooth specimen TMF data to the assessment of real service components with small features causing local stress concentration.

This paper contains two major parts, namely the description of the novel experimental technique and crack growth results shedding light on the mechanisms and kinetics of TMF in single crystals. The new experimental approaches reported in this paper are as follows: (i) notched test method and procedure for TMF crack growth; (ii) successful demonstration of induction thermography for capturing crack growth verses cycle count and subsequent analysis of that data; and (iii) fast cycle thermomechanical fatigue testing using active cooling allowing 30 s heat up and 30 s cooling under sinusoidal command and feedback response.