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Deformation and damage mechanisms during thermal–mechanical fatigue of a single-crystal superalloy

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Abstract

The deformation and damage mechanisms arising during thermal–mechanical fatigue (TMF) of the single-crystal superalloy CMSX-4 have been investigated, both in the virgin condition and after long-term exposure at 1000 °C. Fundamental differences in the mechanical response due to ageing have been discovered, which are attributed to the tendency for the precipitation of topologically close-packed phases during deformation. In the virgin condition, the deformation during TMF is very localized and concentrated to twin bands which extend over the complete cross-section of the specimen; at the interception of these bands, the material is prone to recrystallization. The aged material on the other hand shows a much more dispersed deformation behaviour in which the length and thickness of the twins are much smaller and no recrystallization is found. Instead, significant local misorientations—implying crystal rotation—are observed in the aged material after rupture.

Keywords: Thermal–mechanical fatigue; Deformation mechanisms; Twinning; Recrystallization; Single crystal superalloy

1. Introduction

Nickel-based superalloys are designed to withstand extreme conditions of temperature and loading during operation [1]. This is particularly the case for the airfoils and vanes employed in advanced gas turbines, which are subjected to very significant and time-dependent stress fields during service, whilst being required to survive for many years before scheduled removal during engine refurbishment. The origin of the stresses is the temperature gradients which are generated in the airfoil during engine start-up and shut down, or else the temperature gradients within cooled airfoils arising from steady-state operation. The accumulation of such strain and temperature cycles leads to the possibility of failure by thermal–mechanical fatigue (TMF), which must be avoided by appropriate design of component geometry and choice of operating conditions.

Thermal–mechanical fatigue is growing in importance because gas turbines are being operated under ever more arduous conditions, to reduce fuel usage and CO_2 emissions and to maximize performance. Thus, although critical hot section components have traditionally been designed to resist creep failure, the deformation characteristics under TMF conditions are now just as important and need to be understood and quantified if component lifetime estimates are to be accurate. Unfortunately, at this stage relatively little is known about the degradation mechanisms occurring under TMF conditions, particularly when the superalloys are used in single-crystal form; more fundamental studies are needed to elucidate them. A number of factors are known to be important. Broadly speaking, TMF failure is promoted when plastic strains cannot be

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accommodated at low temperatures and creep deformation and/or oxidation occurs at high temperatures. However, microstructural stability plays a role and it is now established that there are important interactions between the degradation mechanisms occurring at high and low temperatures. This was illustrated for CMSX-4 in Ref. [2] where it was shown that the material degradation during out-of-phase (OP) TMF with a maximum temperature of 1000 °C led to different mechanical behaviour between 100 and 400 °C; crack initiation life was reduced by about a factor of 3 when the minimum temperature was reduced from 400 to 100 °C despite the maximum temperature and the mechanical strain range remaining unchanged. Thus, in order to generate results in the laboratory which are applicable to engine conditions, one must use a minimum test temperature as close as is practical to ambient, in order to avoid non-conservative results.

The research reported in the present paper was conducted with the above in mind. The thermal–mechanical fatigue behaviour of the single-crystal alloy CMSX-4 is investigated under OP loading in the 100–1000 °C temperature range. Since it seems likely that high-temperature exposure at the very hottest part of the cycle will be detrimental, the effect of introducing a dwell period at that point is also studied. As expected, the stabilized stress–strain hysteresis loop is indeed influenced by the high-temperature hold, but some fundamental differences in the deformation and degradation behaviour have been discovered.

2. Background

Although TMF testing has been carried out for over 20 years with many aspects of it studied in detail [3–5], standards for TMF testing are either relatively new or else are still being finalized [6–8]. In principle, TMF testing involves cycling of the temperature T and mechanical strain ε_{mech} with different phase shifts. In the present study, the OP TMF case will be considered, in which the material undergoes creep relaxation in compression at high temperatures and plastic deformation in tension at low temperatures. A schematic illustration of the stress–strain behaviour corresponding to OP-TMF is given in Fig. 1. This cycle was studied since it typically represents the situation for the hottest location of a critical component, e.g. a so-called "hot-spot" on a turbine blade airfoil or platform due to insufficient cooling. Because of its higher temperature compared to the surroundings, the "hot-spot" wants to expand but is constrained by its surroundings, thus leading to compressive stresses during steady-state. If inelastic deformation occurs, high tensile stresses will develop during shut-down. Thus, as creep is always present when engineering components are subjected to TMF conditions, it is common to also introduce a dwell period at the maximum temperature in the test. The length of the dwell period can vary from a couple of seconds to several hours, but for practical reasons the dwell time in laboratory tests is often much shorter than the typical time of operation for the component of interest. This is especially the case for hot components in industrial turbines where the average time between start and stop can be up to 500 h.

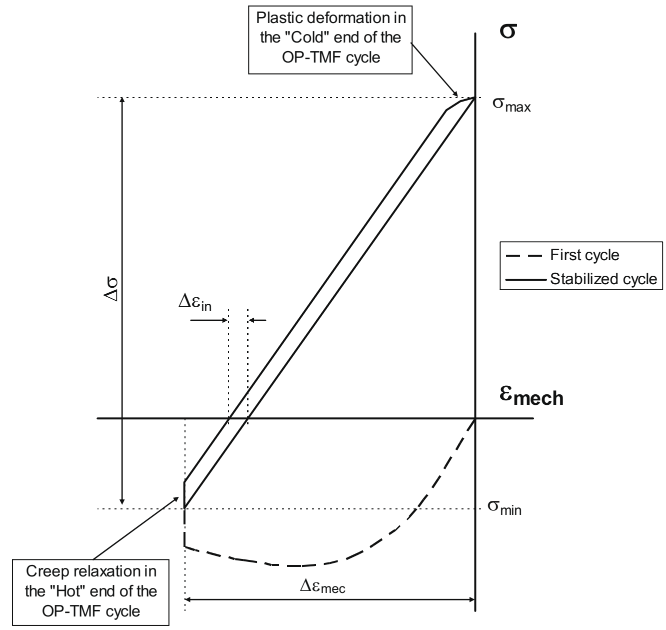

Fig. 1. Schematic illustration of stress vs. strain during OP-TMF.

Most TMF tests are conducted in strain control using servo-electric or servo-hydraulic testing machines where induction heating and forced air cooling is used in order to cycle the temperature [9,10]. In order to have control of the mechanical strain ε_{mech} it is necessary to compensate for the axial strain induced in the specimen due to thermal cycling. Therefore the thermal strain ε_{th} must be subtracted from the measured total strain ε_{tot} as described by Eq. (1):

$$\varepsilon_{mech} = \varepsilon_{tot} - \varepsilon_{th} = \varepsilon_{tot} - \alpha(T - T_0) \quad (1)$$

where T_0 is the reference temperature at the beginning of the test, T is the test temperature and α is the coefficient of thermal expansion. Due to the need for continuous dynamic temperature measurement, TMF is somewhat more complex than other more traditional testing techniques. This is probably the reason why—despite its importance as a failure mode for high-temperature components subjected to intermittent operation—the TMF behaviour of high-temperature alloys is reported rather infrequently despite its great practical importance.

3. Experimental procedure

The single-crystal nickel-based superalloy CMSX-4, one of the most commercially important alloys for gas turbine applications, was chosen for the present work. The chemical composition is Ni–5.65Al–9.6Co–6.4Cr–0.11Hf–0.61Mo–2.9Re–6.6Ta–1.02Ti–6.4W (wt.%). The material was solution heat treated at 1275 °C for 8 h followed by a two stage ageing process with 3 h at 1100 °C and