International Journal of Solids and Structures 000 (2016) 1–19

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Isothermal low-cycle fatigue and fatigue-creep of Haynes 230

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ARTICLE INFO

Article history:
Received 12 December 2015
Revised 1 March 2016
Available online xxx

Keywords:
Haynes 230
High temperature LCF
Fatigue-creep
Fatigue life
Dynamic strain aging

ABSTRACT

Service temperature of airplane gas turbine engine combustors fluctuates between ambient to as high as 982 °C, during which structural constraints induce cyclic stresses and strains resulting in thermo-mechanical fatigue damage accumulation in the combustor liner. In order to substantially improve the current design methodologies or low-cycle fatigue (LCF) life predictions of such high-temperature components, it is essential to develop an experimentally validated advanced constitutive model. This requires a broad set of fatigue data of the combustor liner material, Haynes 230 (HA 230) – a nickel-based superalloy, to characterize its fatigue failure responses. Hence, a systematic set of isothermal experiments are conducted prescribing uniaxial strain-controlled loading cycles, with and without a compression peak strain-dwell, with and without a mean strain, at seven different temperatures in the range of 24–982 °C and at three strain rates. The experimental responses are critically examined to explore various fatigue failure responses of HA230, which is a complex material showing unique fatigue-creep, strain rate sensitivity, strain range dependence, temperature dependence and dynamic strain aging (DSA) properties. DSA is found to occur in the temperature domain 427–760 °C. Isothermal experimental responses at different strain rates show that HA 230 can be considered rate-independent at and below 760 °C. However, stress relaxation is observed at lower temperatures up to 649 °C during the peak strain-dwell period. Finally, fatigue lives of HA 230 from the isothermal experiments are found to decrease with increase in temperature. These experimental responses are presented and challenges in constitutive model development are discussed.

1. Introduction

Efficient operations of aerospace, automobile, nuclear power and chemical industries require the use of high temperature components, such as, gas turbine combustors, heat exchangers and steam generators. The design of such components that experience thermo-mechanical fatigue (TMF) at very high temperatures is extremely complex because of the interactions between several failure mechanisms. Due to start-up and shut-down cycles, repeated thermo-mechanical stresses are induced resulting in the low-cycle fatigue (LCF) resistance of high temperature components, causing them to gradually degrade. In the present study, the component of interest is the combustor liner in an airplane gas turbine engine, which are fabricated from sheets of Haynes 230 (HA 230) as shown in Fig. 1. HA 230 is a Ni-Cr-W-Mo solid-solution strengthened superalloy, which possesses excellent high temperature strength and outstanding resistance to oxidation in deleterious environments. During turbine engine operation, the combustor components are subjected to TMF loading conditions, with temperature fluctuating from ambient to as high as 982 °C.

A typical airplane flight consists of a start-up phase during take-off which leads to temperature rise, followed by an almost steady phase of flying, when the operating temperature is maximum and remains relatively steady, and finally the landing and shut-down phase leads to temperature drop to ambient. This temperature fluctuation coupled with geometric constraints of the combustor liner (Fig. 1) leads to compressive strains being induced in the vicinity of hot spots as they try to expand. Such a loading cycle is known as out-of-phase thermo-mechanical fatigue (OP-TMF), which is defined as the decrease in axial strain (compressive strain) with the increase in temperature (Zhang et al., 2002, Yaguchi et al., 2002a, 2002b, Hasselqvist, 2002, 2004, Lee et al., 2014, Jones et al., 2014). The flight time of an airplane can be as short as 30 min to as long as 16 h, during which significant creep deformation occurs. The cyclic nature of high temperature OP-TMF loading with long dwell-periods, induced by repeated airplane flights, results in a complex creep-fatigue damage interaction. This

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http://dx.doi.org/10.1016/j.ijsolstr.2016.03.011
0020-7683/

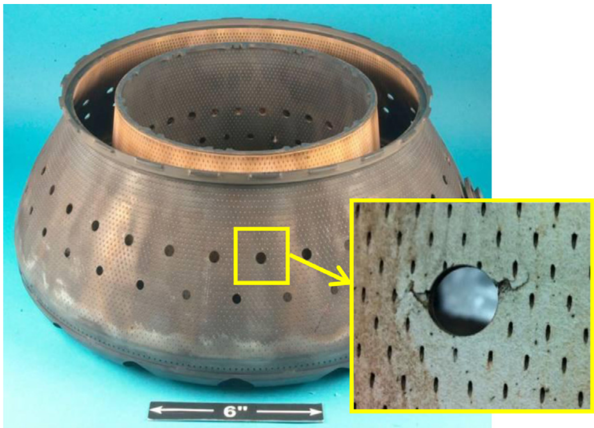

Fig. 1. HA 230 combustor liner showing cracking due to TMF.

creep-fatigue interaction is further complicated by repeated high-temperature exposures resulting in the creation of "hot spots" surrounding the effusion and dilution holes of the combustor liner (see Fig. 1). These hot spots initiate low-cycle fatigue cracks as shown in the inset of Fig. 1, which often causes the actual service life to be as low as one-fifth of the predicted design life of combustor liners using current design-by-analysis methodologies.

Despite the use of high temperature resistant superalloys, such as HA 230, premature cracking of combustor liners significantly increases the operation and maintenance expenses of jet engines. Hence, accurate TMF life prediction and development of an improved design-by-analysis methodology for high temperature components is of paramount importance. Material responses in these critical components involve various time-dependent processes such as creep, fatigue, creep-fatigue interactions, thermo-mechanical fatigue, cyclic creep or ratcheting, dynamic strain aging (DSA), and oxidation which influence the integrity of the high temperature components (Rodrigues and Rao, 1993; Dedekind and Harris, 1996; Xie et al., 2006; Sadowski and Golewski, 2011; Jones et al., 2014). It is essential to understand these complex material responses under realistic loading conditions and harsh environments, in order to substantially improve the current design methodologies.

According to the current industry practice, the fatigue life of a component is estimated based on either simple elastic or simplified inelastic analysis using commercial software, which lacks fidelity in the service life predictions. LCF life of critical high temperature components in aerospace, as well as, chemical, automobile and power generation industries should be predicted with a reasonable accuracy for their efficient and economic operation. This in turn needs the development of a robust constitutive model capable of describing different time and temperature-dependent material responses over a wide range of temperatures and loading histories. Such a constitutive model will allow development of reliable life prediction techniques for critical components.

The first step towards the development of a robust constitutive model for HA 230 is to develop a comprehensive database of material responses under various loading conditions and temperature spectrum encompassing the operating service conditions of the combustor liner. Researchers have characterized the LCF behavior of various high temperature alloys, such as: Inconel 617, HA 188, Nimonic PE-16, 316L stainless steel, and modified 9Cr-1Mo steel under different isothermal temperatures, strain rates, loading histories with or without dwell-period, strain range parameters etc. as elaborated below. Most of the earlier high-temperature LCF research works primarily focused on the micromechanical features of the fatigue responses from a limited number of experiments. These fatigue characterization studies on high temperature alloys revealed that, generally increasing the temperature, decreasing the strain rate, or introducing a hold time causes a reduction in fatigue life (Rodriguez and Rao, 1993; Rao et al., 1988a, 1988b). Micromechanical evidences were provided to reveal the time-dependent damage mechanisms, such as creep, creep-fatigue crack initiation, DSA, and oxidation processes.

Experimental studies on high temperature alloys also demonstrated cyclic hardening-softening responses (Rao et al., 1988b; Hasselqvist, 2002, 2004), DSA (Rao et al., 1988b; Mannan, 1993), strain rate sensitivity (Rao et al., 1988b; Mannan, 1993; Valsan et al., 1994; Rao et al. 1995), and stress relaxation during LCF dwell-periods (Rao et al., 1988b; Lu et al., 2005; Chen et al., 2013). Rao et al. (1988a) presented stress relaxation of Inconel 617 at 950°C and 0.6% strain range LCF loading with different dwell-periods (up to a maximum of 120 min) with strain-dwell at tension-peak, compression-peak, and both tension and compression peaks. In the same study, the positive strain-rate sensitivity of Inconel 617 at 950 °C was ascertained. Again, much of their experimental study focused on the crack initiation processes when fatigue and creep damages interacts. In another study by Rao et al. (1988b), the influence of strain rate (10^{-6} to 10^{-3} s^{-1}) and temperature (750, 850, 950 °C) for Inconel 617 were investigated. DSA characterized by serrated flow was also shown by Rao et al. (1988b) at 750° and 850 °C for higher strain rates. They also demonstrated that the stress amplitude response is either cyclically hardening or softening, or a combination of the two depending on the level of temperature.

HA 188 was studied across a spectrum of temperature (25–1000 °C) for a strain range 0.8%. This Ni-based alloy showed DSA in the temperature regime of 300–750 °C. DSA causes the alloy to cyclically harden significantly while also displaying negative strain rate sensitivity (Mannan, 1993). Negative strain rate sensitivity resulted in greater cyclic stress amplitude responses for slower strain rates. Hasselqvist (2004) reported the austenitic carbide precipitating (ACP) mechanism of various alloys showing the cyclic responses of HA 188 (Castelli and Rao, 1996), 316L stainless steel (Alain et al., 1997), and HA HR-120 (He et al., 2002) across a wide range of temperatures for constant strain ranges and strain rates. More recently, Lu et al. (2005) and Chen et al. (2013) have investigated HA 230 for different temperatures, strain ranges, and dwell periods. The influence of dwell period (0, 2, 10, and 60 min) was presented at 816 °C and 927 °C showing the effect on cyclic hardening/softening behavior as well as the fatigue life. Inconel 617 and HA 230 responses at 850 °C were compared by Chen et al. (2013) showing that for all fatigue-creep tests HA 230 exhibited a longer life than Inconel 617. In the same study two fatigue-creep life prediction methods, linear damage summation and frequency-modified tensile hysteresis energy modeling, were evaluated. In addition, few TMF experimental studies on high temperature alloys, in particular nickel-base superalloys, have been carried out (Kleinpass et al., 1996; Chan and Lindholm, 1990; Chan et al., 1989; Moreno and Jordan, 1986; Benallal and Cheikh, 1987; Zauter et al., 1991; Lee et al., 2014; Jones et al., 2014).

The literature review above demonstrates that the high-temperature LCF experimental data of Ni-based superalloys, especially HA230, is limited and insufficient for constitutive model development and validation. Past studies primarily concentrated on the microstructural characterization of fatigue failures and not the cyclic stress-strain evolution of these superalloys under LCF testing conditions for a wide range of parameters, including strain range, strain rate, temperature, mean strain effect and hold time effect. Due to the lack of a broad set of cyclic responses of HA 230, which is essential for constitutive model development and validation, this study performed over 120 LCF experiments varying the test conditions for developing a comprehensive HA 230 database, not available in the literature. In this experimental study,