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A physics-based model for evaluating hot compressive dwell effects on fatigue crack growth in 319 cast aluminum alloys

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ABSTRACT

Fatigue crack growth under hot compressive dwell (HCD) conditions, a case of creep–fatigue occurring under compressive loading, is an important failure mode in high temperature environments. Creep-induced tensile residual stresses gradually built up in the vicinity of the crack are considered to be a key factor contributing to crack growth under HCD conditions. To understand and quantify this effect, a simple physics-based model has been developed, in which the residual stress contributions associated with creep and plasticity are added to the elastic response of the material to predict crack growth under HCD conditions using Linear Elastic Fracture Mechanics (LEFM). Test of a cast 319 Al alloy has been conducted both for material characterization and under baseline and HCD conditions to evaluate the model. With HCD, the crack growth rate was increased on average by a factor of about 6, which is consistent with model predictions.

1. Introduction

Materials under service loads at elevated temperature (>40% of the absolute melting temperature) are typically subject to creep, an accumulation of inelastic strain that occurs over time that often contributes to component damage in automotive engines, jet engines, nuclear power plants, and other applications. Creep–fatigue interactions occur when cyclic loads dwell at combinations of elevated temperature, stress and time sufficient to result in significant amounts of creep deformation which can play a role in crack initiation and growth, compromising structural function and integrity. This can occur isothermally or more generally in the course a Thermo-Mechanical Fatigue (TMF) duty cycle.

A large body of literature addresses the role of creep in isothermal fatigue and TMF to the point of crack initiation [1]. A smaller body of work addressing subsequent crack growth, largely focuses on crack tip creep and environmental effects associated with hot tensile dwell or in-phase TMF, where the crack is open during the elevated temperature portion of the cycle for a substantial period of time. This type of crack growth is often characterized by highly localized creep [2,3] and/or environmentally-assisted fatigue crack growth phenomena [4,5] at the crack tip. A common approach is to represent the total crack growth rate, da/dN_{tot} as the sum of time-independent and time-dependent crack growth rates [6].

$$da/dN_{tot} = da/dN + \Delta t_{dwell}(da/dt) \quad (1)$$

Far less attention has been given in the literature to hot compressive dwell crack growth, including out-of-phase TMF crack growth. Yet this is an important phenomenon in automotive and aerospace engines, Rankine cycle Power plants, and other applications, particularly at geometric or thermal stress concentrations. For mode I cracking, one would expect $da/dt = 0$ during compressive dwell, so crack growth acceleration due to HCD must involve a different mechanism than tensile dwell.

In fact, HCD can result in crack growth when the load cycle has little or no applied tension, and Eq. (1) would predict zero growth. Rhymer [7] and his colleagues studied HCD crack growth in a circular plate cyclically heated at the center in a burner rig with no other applied load. Residual stress build up associated with viscoplastic deformation was modeled using finite element analysis, including contact elements to simulate the closed crack during the hot portion of the cycle. The resulting residual (positive) K_I during the cool part of the cycle was calculated numerically as a function of crack length and shown to be largely consistent with the observed initially rapid, but then self-arresting growth behavior. The method, while useful for exploring the behavior, was rather cumbersome and in the end quite approximate at least for the burner rig, but the underlying residual stress mechanism appears to be sound.

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In this effort a more tractable means is sought to predict HCD crack growth behavior. Rhymer's work illustrates that neglecting the effect of HCD on crack growth can be non-conservative. While in the burner rig the crack was self-arresting, such is not always the case. Further, when HCD-induced cracks do appear in service, it would be useful to be able to assess whether they are likely to self-arrest, or even design for self-arrest.

2. Problem description: the hot compressive dwell phenomenon

The HCD phenomenon in an engine block occurs as schematically illustrated in Fig. 1. One side of the combustion chamber wall is heated and the other is connected to a water circuit, as shown in Phase 1. When the engine starts, the combustion chamber wall gradually heats up to about 250 °C, and expansion occurs in this hot area. On the opposite side, the water circuit cools down the engine. A temperature gradient and a dimensional variation from the hot area to the cold area are generated. The expansion in the hot area is constrained by the nearby cold area, as shown in Phase 2, resulting in a hot compressive state. Under design loading, local compressive yielding might occur. Prolonged operation in this HCD condition, can further result in creep deformation over time, as shown in Phase 3. After shutdown, the combustion chamber cools down, and its walls begin to contract. However, provided the tensile stress does not exceed yield (a very real possibility to be discussed later), the permanent deformation that occurred during high temperature dwell is retained in this stage, because creep is inactive at the lower temperature. Due to the rigidity of the whole body, the contraction is constrained by the adjacent undeformed material, as shown in Phase 4, resulting in tensile residual stress in the combustion chamber wall. As the combustion chamber repeatedly heats and cools over a period of usage, permanent deformation and tensile residual stresses continue to accumulate during the thermal cycles. These residual stresses sum with cyclic operational stresses, thereby accelerating crack initiation and propagation.

While for simplicity the illustration depicts a smooth area, representing the cylinder wall, the same phenomenon occurs in the cylinder head, where valve passages and other stress concentrations increase the stress levels, compounding the problem. It is in these notched features that cracks are most likely to appear. Similar notched features are common in many applications involving HCD.

3. A simple model for residual stress accumulation

The stress dieout adjacent to such a feature (in this case a hole) is illustrated schematically in Fig. 2 for the maximum and

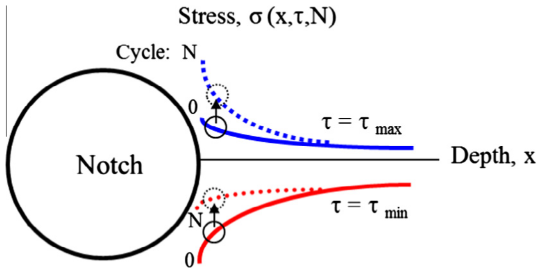

Fig. 2. Illustration of stress shift adjacent to notch associated with creep relaxation.

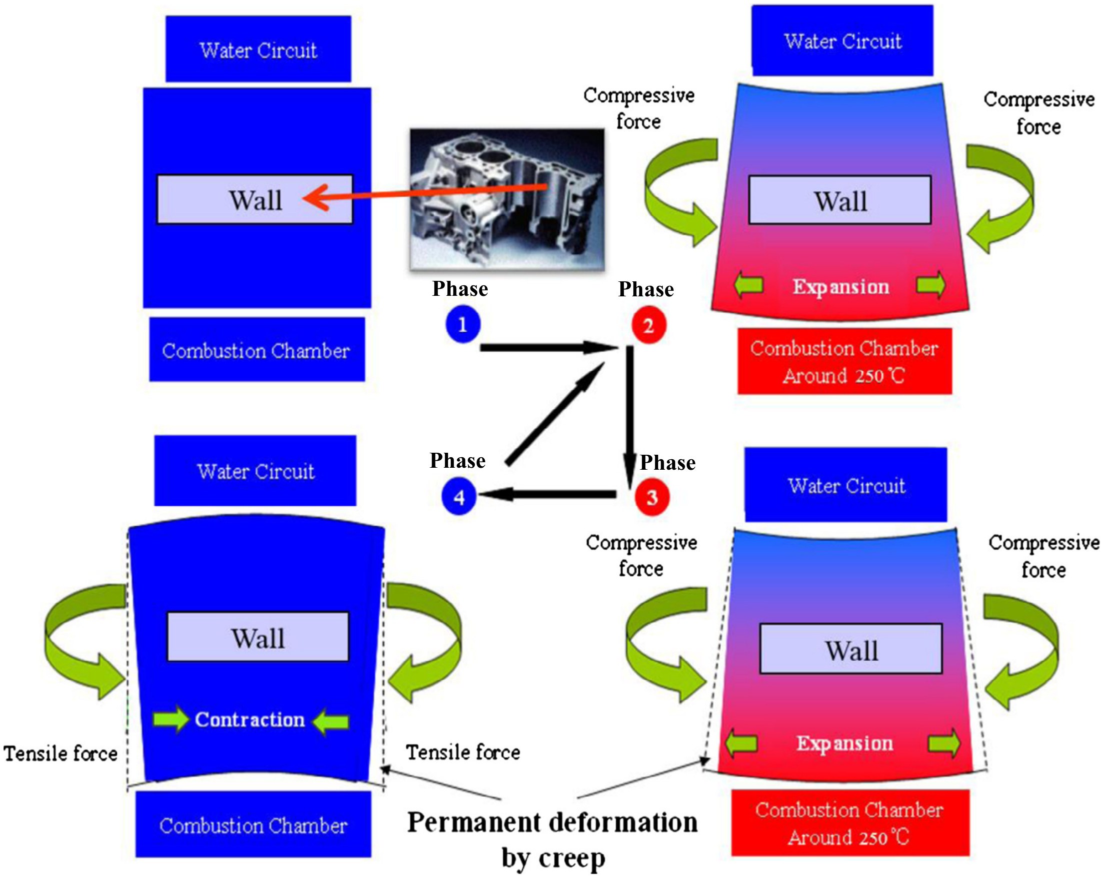

Fig. 1. Schematic illustration of hot compressive dwell.