A PHENOMENOLOGICAL MODEL FOR CREEP CRACK GROWTH RATE BEHAVIOR IN FERRITIC STEELS

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Abstract

A phenomenologically based micro-mechanics model is described that rationalizes the effects of test temperature and microstructural variables such as grain boundary particles on the creep crack growth rate (CCGR) behavior of ferritic steels. The model predicts that as the average spacing between particles that initiate creep cavities on grain boundaries decreases, the CCG rates are expected to increase. Also, CCGR data at several temperatures can be collapsed into a single trend using the newly proposed temperature compensated creep crack growth rate trend derived from the proposed model. The model is evaluated using data for Grade 22 and Grade 91 steels.

1. Introduction

The rate at which a crack in a structural component is expected to grow under high temperature creep conditions is a critical aspect of a fitness for service (FFS) evaluation. Crack growth rate is an essential input for a temporal understanding of when fracture is expected to occur or when a certain threshold will be exceeded, warranting an inspection of the component. Two materials are prioritized in this paper: Grade 22 (2.25Cr-1Mo) and Grade 91 (9Cr-1Mo-V-Nb-N) ferritic steels.

2. A Phenomenological Model for Creep Crack Growth

A model first proposed by Wilkinson and Vitek and developed further by Saxena and Bassani referred to as WVSB model is presented and evaluated in this paper. Creep damage ahead of the crack tip is assumed to be in the form of an array of creep cavities with radii of $\rho_1,\ \rho_2 \ldots.\rho_i \ldots \rho_N$ that are spaced by a center-to-center distance of 2b. The cavities are assumed to nucleate on the grain boundary facets that are aligned normal to the loading direction and have an initial radius of ρ_N, which corresponds to the radius of the nucleating particle. These cavities grow at a rate constrained by the kinetics of power-law creep under the crack tip stress environment. When the cavity closest to the crack tip approaches a critical radius, it coalesces with the crack tip and the crack is believed to have advanced by a distance 2b. All successive cavities grow and move closer to the crack tip while the one nearest to the crack tip is coalesces to become part of the crack. A steady-state crack growth rate is established and described by equation (1).

$$\frac{da}{dt} = \beta\alpha(n)(A)^{\frac{1}{n+1}}\left(\frac{C^*}{b}\right)^{\frac{n}{n+1}} \quad (1)$$

The constant β includes the angular terms in the crack tip stress fields and can be treated as a regression constant. $\alpha(n)$ is shown to be ≈1.3 for $5 \leq n \leq 10$ and thus can be made part of the regression constant. If b_0 represents the inter-cavity spacing in a virgin or unused material, equation (2) can be rewritten as:

$$\text{or,} \qquad \frac{da}{dt} = C_1(A)^{\frac{1}{n+1}}(b_0/b)^{\frac{n}{n+1}}(C^*)^{\frac{n}{n+1}} \quad (2)$$

Where, $C_1 = \frac{\alpha(n)\beta}{(b_0)^{\frac{n}{n+1}}}$.

In equation (2), the term $(A)^{\frac{1}{n+1}}$ compensates the CCGR for temperature. For b less than b_0, the creep crack growth rate is expected to accelerate. Thus, a microstructural length dimension that can evolve during service and is potentially measurable, is explicitly included into the creep crack growth rate equation. If, during service, new grain boundary particles appear due to exposure to service temperatures reducing the value of b, the CCGR is expected to increase with the evolving microstructure.

The constant A is a strong function of temperature. However, when it is raised to a power of 1/(n+1), where n ranges between 7 and 13 for ferritic steels, the dependence of da/dt on A becomes weak. Never-the-less, the dependence of da/dt on temperature can be rationalized by defining a reference temperature, T_0, and CCGR rates at other temperatures are referenced to T_0, as in equation (3). In equation (3), we have also replaced C^* with a more general parameter C_t that is applicable to small-scale-ceep conditions and becomes identical to C^* under steady-state creep conditions. This parameter also permits the inclusion of creep-fatigue crack growth rate data at various hold times on the same plot.

$$\frac{da/dt}{[A(T)/A(T_0)]^{\frac{1}{n+1}}} = C_0\left(A(T_0)\right)^{\frac{1}{n+1}}(C_t)^{\frac{n}{n+1}} \qquad (3)$$

Where, C_0 is the value of C at the reference temperature and $\frac{da/dt}{[A(T)/A(T_0)]^{\frac{1}{n+1}}}$ is the temperature compensated CCGR rate. Figure 1 shows the correlation between the temperature compensated creep and creep-fatigue crack growth rates at various temperatures, hold times during fatigue cycling in new and ex-service Grade 22 materials. The reference temperature in this case is 540 ^{0}C. All data over several orders of magnitude in growth rates fall within a narrow scatter band. No significant differences were found in the data trends for new and ex-service materials. However, that was not always the case, such as with weldments for Grade 22 steel where there are clear differences in the CCGR behaviors of ex-service and new materials taken from the heat-affected zone (HAZ) and fusion line (FL) regions. The CCGR trends from codes such as BS7910 and API for Grade 22 base metal fit these data well taken from a variety of sources.

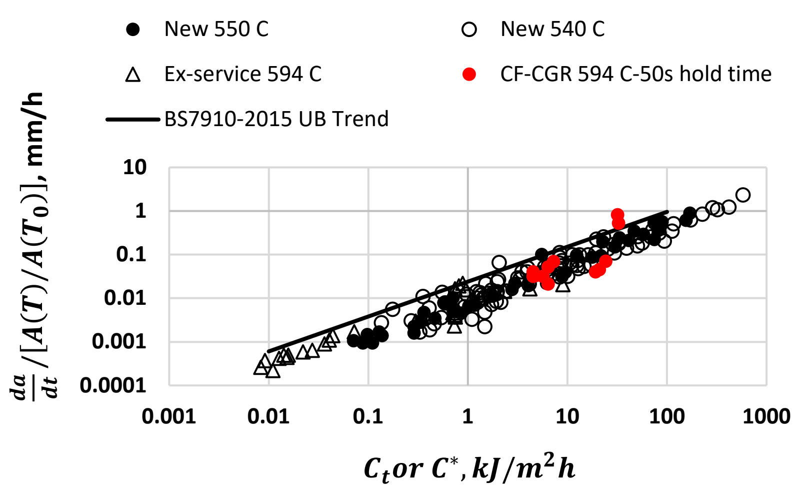

Fig. 2 –Temperature compensated base metal CCGR and CF-CGR behavior as a function of C_t for hold times of 50s for Grade 22 steels at various temperatures.

In the case of Grade 91 materials we see different creep crack growth rates between ex-service and new materials in the base metal regions. Parker and Siefert have argued that the tendency for higher creep crack growth in some Grade 91 materials are due to variations in chemistry and microstructures even in new materials where some heats are creep damage resistant while others are creep damage prone. These differences are excercabated by exposure to elevated temperatures in the creep regime during service.

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