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Constitutive creep–fatigue crack growth methodology in two steels using a strip yield model

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ABSTRACT

A creep–fatigue crack extension model based on a strip-yield methodology is presented and model predictions compared to experimental data over a range of temperatures, stresses and materials. In addition, a constitutive creep damage model for AISI 316L is developed. An empirical model based on the C^* parameter and a constitutive model will be used to predict crack extension and compared. Advantages and limitations of the empirical creep model and the constitutive model are highlighted. In view of these limitations and the experimental comparisons, future development actions are recommended.

1. Introduction

Engineering analysis of failure in metals has predominantly considered either a constant (steady) load using the techniques of fracture mechanics or a cyclic (time varying) load using the techniques of fatigue analysis. Actual service conditions for most components are typically a combination of these two loading modes. The importance of analyzing the combination of fatigue and creep damage is highlighted by certain service conditions during long-term exposure to high temperature and corrosive chemistry. As demand drives industries like energy and aerospace more frequently toward solutions in these conditions, models that can successfully predict damage evolution due to combined steady and cyclic loads are essential.

ASTM Grade 91 (modified 9Cr–1Mo) steel is a high strength alloy steel designed for high resistance creep, corrosion and stress corrosion cracking [1]. Since its development in the 1970s, modified 9Cr–1Mo steel has been a popular choice for components serving in petrochemical plants, sodium cooled fast reactors (especially in steam generator components, where stress corrosion cracking is a concern [2]), for both thermal and nuclear power plants and fast breeder reactors [1]. These characteristics, in addition to a high resistance to the detrimental effects of large doses of radiation, also make modified 9Cr–1Mo steel appealing to designers of fusion reactors [3]. AISI 316L stainless steel is a corrosion and fatigue resistant steel. It has long been used for a variety of applications such as nuclear power, chemistry, aerospace, food processing and tools [4]. More recently 316L has become a popular material choice for biomedical applications due to its high fatigue strength and ductility [4].

Based on a yield strip method originally proposed by Dugdale [5], the authors presented a creep, fatigue and combined creep–fatigue crack growth model [6]. This model was benchmarked to experimental creep–fatigue data for modified

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Nomenclature

a	crack length
$\dot{a}$	creep (time dependent) crack extension rate
A	Norton power law constant
b	plate half width
B	plate thickness
C^*	Contour integral analogous to J-integral
d	combined length of the crack and creep process zone
D_s	damage caused by depletion of the solid solution of the Fe_2Mo laves phase
D_p	damage due to precipitate particle ($M_{23}C_6$) coarsening
D_N	damage due to void nucleation and crack formation
E	elastic modulus
G	shear modulus
$I_{N'}$	non-dimensional function of the plastic strain hardening exponent
k_Λ	fitting constant in the constitutive creep correlation
K	crack tip stress intensity factor (SIF)
$K_{I\sigma}$	SIF due to remotely applied load
K_{I0}	SIF due to compressive stress in the plastic zone
M	Taylor factor
n	Norton power law exponent
N	number of applied cycles
N'	plastic strain hardening exponent
P	applied load
w	yield strip width
v_g	dislocation glide velocity
V_i	displacement of the ith yield strip
$\dot{\Delta}^c$	load line displacement rate due to creep
ΔK	SIF range
ε_f^*	strain at fracture
$\dot{\varepsilon}_s$	secondary creep strain rate
η_p	geometric function
λ	material grain size
ρ	creep process zone length
ρ_m	mobile dislocation density
$\dot{\rho}_m$	mobile dislocation density rate
σ	applied stress
σ_0	flow stress
$\dot{\phi}$	crack tip opening displacement rate
$\frac{da}{dN}$	fatigue crack growth rate

9Cr–1Mo steel. Two modeling approaches for creep-crack growth were implemented and compared: an explicit, empirical method and an implicit, constitutive method. The empirical modeling was based on the creep crack extension model developed by Nikbin, Smith and Webster (NSW model) for stable creep crack extension using the crack tip parameter C^* [7]. The NSW model was implemented as a power function of C^*, a parameter analogous to the J-integral proposed by Hutchinson, Rice and Rosengren [8,9] to characterize non-linear elastic material behavior in certain stress/strain fields (known as HRR stress/strain fields) [10,11]. The constitutive model was based on the fundamental mechanisms that drive the creep phenomena, such as dislocation density and mobility and it was first proposed in [12].

Other authors also used C^* as a crack-tip driving force to predict creep–fatigue crack growth rate data. Narasimhachary and Saxena conducted creep–fatigue crack growth experiments in modified 9Cr–1Mo [13] and compared the results to predictions using a C^*-based model. They found that the predictions from this model were more accurate than predictions based on ΔK. Thus, they suggested that the model predictions could be improved by conducting load-line displacements tests for use in calculating C^* [13]. Wasmer, Nikbin and Webster compared the results of creep–fatigue crack growth experiments in 316L stainless steel to predictions from a modified NSW model [14]. C^* was estimated using the reference stress method and Wasmer et al. found that the accuracy of the analytical predictions were strongly dependent on the reference stress correlation used.

The present study will compare both the results from the empirical and constitutive creep model to experimental creep crack extension data in modified 9Cr–1Mo steel. Material constants will be developed and the constitutive creep model will be compared to experimental creep crack extension data in 316L stainless steel. Finally, model assumptions will be discussed and analyzed.