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A diffusion driven carburisation combined with a multiaxial continuum creep model to predict random multiple cracking in engineering alloys

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ABSTRACT

A diffusion-based coupled oxidation, intergranular damage and multisite randomised crack growth model for environmentally assisted oxidation/carburisation and creep time dependent material is proposed. A combined grain boundary and grain mesh structure is employed for simulating surface hardening and intergranular cracking resulting from a surface gas/solid carbon diffusion and bulk creep interaction by assuming variations in their strength ratios. Using 316H properties at 550 °C the predicted surface intergranular cracks, due to both carburisation and creep, and subsequent crack growth are analysed in terms of their rupture and failure strains are compared to as received 316H data to validate the model.

1. Introduction

Environmental time-dependent creep damage and oxidation/carburisation of engineering alloys encompasses a relatively wide scope in the way it can affect the structure. Mechanisms such as creep cracking [1–5] and oxidation/carburisation/nitriding [4–13] have in common a 'rate dependent' damage inducing component. It has been shown that three main categories of damage rate dependencies exist in the oxidation processes. The extreme case is linear or accelerating rates of empirical laws damage which can occur at extreme temperatures and environments. The second and third can be described by logarithmic and parabolic relationship [6–13] which essentially describe the rate of damage as continually decreasing with time. In some cases the process can deplete or harden the surface and/or can develop a self-healing/protection mechanism, depending on the type of alloy, environment and temperature and oxidation mode which prevents further surface damage. However regardless of the rates of damage one important aspect of these load independent damage processes is that the induced surface grain and intergranular damage may provide initiation sites for the development of stress concentrations tending to enhanced cracking at high temperatures (see Fig. 1a). As shown in Fig. 1b, for the 316H steel [14], clear

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Nomenclature

α	plastic hardening multiplier
β	oxidation damage power law exponent
φ	integral constant for solution of Fick's second law
A	Norton's creep constant
D	Fick's second law diffusivity coefficient or diffusivity in mm^2/s
D_o	proportionality constant for diffusion (mm^2/s)
ω^{cr}	creep damage
ω^{env}	environmental/oxidation/corrosion damage
ω^{ran}	random distribution of damage
ω^{tot}	total damage
ω_p	parabolic oxidation damage index
ω^x	damage distribution density
^{erf}	error function in Fick's law
E	elastic (Young's) modulus
h	σ_m/σ_e
H_{v1}	hardness of fully damaged region
H_v	hardness distribution indicating damage index
H_{v0}	hardness of as received material
J	the diffusion flux with units $moles/cm^2/s$
$c(x, t)$	the gas concentration
c_{crit}	critical concentration of diffusion in substrate that causes full damage
c_s, c_o	the surface and the equilibrium gas concentration in cm^3 or wt%
WH, NH	with and without surface hardening
$X = ½(c_s + c_o)$	carburisation distance from the surface mm
x	distance from surface
Q	activation energy (kcal/mol)
R, T	Boltzman constant (cal/mol K), and temperature (K)
k_p, k_e	parabolic and logarithmic oxidation multiplier
n	secondary creep stress exponent
ε_f	material ductility
ε_f^*	multiaxial creep ductility
$\varepsilon^{cr}, \dot{\varepsilon}^{cr}$	creep strain and creep strain rate
$\dot{\bar{\varepsilon}}^{cr}$	effective creep strain rate
r_n	random number index between ±0.1 deviation from mean
t	time
t_r	uniaxial rupture time
x_i, x_w	distance from the surface and width of the specimen
σ	nominal stress
σ_m	the mean (hydrostatic) stress
σ_e	equivalent (von Mises) stress
σ_{p0}	plastic hardening initial yield stress
σ_Y	yield stress
Ω_G, Ω_{GB}	damage threshold $\leqslant 1$, for grains and grain boundaries
y	function of diffusion rate
da/dt	crack growth rate mm/h
C^*, K	the creep (MJ/m^2) and linear elastic fracture mechanics parameters ($MPa\sqrt{m}$)
D^c, ϕ, C, m	material constants for cracking rate correlation
P	applied load
B_n, W, a	net thickness, width and crack length
H, η	geometry dependent constants
$\dot{\Delta}$	creep load-line displacement rate

intergranular damage beyond the oxidised region is present. Hence for the case of superimposed creep or creep/fatigue cracks with applied stress it is likely that the mode to initiate or grow the crack is likely to be enhanced by the initial mode of damage induced in the microstructure by the oxidation/carburisation process. In this paper the damage process will be investigated in parallel with creep damage and crack growth for 316H type stainless steel taking into account factors such as surface carbon diffusion rate, grain boundary creep strength, surface hardening and creep strength.