



Crack tip transformation zones in austenitic stainless steel

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ABSTRACT

Crack tip conditions in SUS 304 austenitic stainless steel are studied using a constitutive model in which the martensitic phase transformation is an integral part. The phase transformation occurring in the crack tip region gives rise to fracture toughening of the material whereby the resistance against crack initiation, as well as the macroscopic material response are strongly altered by the presence of a martensitic phase. The constitutive model employed herein permits studying the transformation zones under different isothermal conditions. Local crack tip conditions and related plastic deformation is confirmed to depend strongly on the varying extent of the martensitic phase transformation at different temperatures. The shape and size of the plastic and transformation zones in the neighborhood of the crack tip are obtained from numerical simulations, as well as derived analytically.

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1. Introduction

Austenitic stainless steels are of major engineering importance in many applications due to their excellent mechanical properties over a wide range of temperatures in combination with good corrosion resistance. This class of steels is also susceptible to diffusionless phase transformation of the austenitic face-centered cubic parent phase into body-centered cubic or body-centered tetragonal martensite under applied deformation. This very rapid transformation is promoted by a lowering of the temperature while higher temperatures restrict martensite formation [1]. Since austenitic stainless steels are used for example in power generating and chemical industries, low-temperature service conditions for these materials are indeed common. If the loading situation is such that fracture is initiated in the material, formation of martensite at the crack tip may delay or even prevent further crack propagation. The increase in fracture toughness due to martensite formation, which has been frequently observed, e.g. in [1–8], is somewhat surprising since the hard martensitic phase is considerably more brittle than the ductile austenite. This transformation toughening and reduction of crack growth rate has been attributed to crack tip shielding and crack tip blunting [9], and crack closure due to roughening of the crack surfaces or due to the crack being subjected to compression by the dilatation in the transformed material [10,11]. In addition, several authors point out that the strongly dissipative process of martensitic phase transformation reduces the energy available at the crack tip for extending the crack [2]. On a micromechanical level, crack initiation is delayed since void nucleation is reduced by the phase transformation, cf. [12], and the growing martensitic phase restricts subsequent void growth [13].

It is also noted that the fracture toughness is not a strictly increasing function of the volume fraction of transformed material, but also a function of temperature, strain rate and the absolute size of the martensite islands that are formed [14,15]. Regarding the latter, based on experimental observations, it was proposed in [16] that smaller regions of martensite restrict

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Nomenclature

b	parameter controlling the non-roundness of the transformation potential surface
\mathbf{b}^r	reversible part of the left Cauchy–Green tensor
c_i	parameters in the transformation threshold function
$c_p^{a,m}$	specific heat of the austenite and martensite phase, respectively
E	elastic modulus
f	yield function
F_{mech}	mechanical transformation driving force
\bar{F}_{mech}	θ -dependent components of F_{mech} from the HRR solution
\tilde{F}_{mech}	θ -dependent components of F_{mech} from the linear elastic solution
F_{chem}	chemical transformation driving force
F_{trans}	transformation threshold function
$\mathbf{F}, \mathbf{F}^r, \mathbf{F}^{ir}$	deformation gradient, its reversible and irreversible components
G	shear modulus
h	transformation potential function
I_1	first invariant of the stress tensor
J_2, J_3	second and third invariants of the deviatoric stress tensor
J^r	determinant of the reversible deformation gradient
K	bulk modulus
\bar{K}	parameter in the transformation potential function
K_I	mode I stress intensity factor
K_σ	stress amplitude parameter in the HRR field
$\mathbf{l}, \mathbf{l}^r, \mathbf{l}^{ir}, \mathbf{l}^p, \mathbf{l}^{tr}$	spatial velocity gradient, its reversible, irreversible, plastic and transformational components
n	exponent in the Ramberg–Osgood hardening law
$r_{pl,tr}$	radius of the plastic and of the transformed zone, respectively, at the crack tip
r, θ	polar crack tip coordinates
R, R_{ct}	radius of the FE-analysis domain and of the inner crack tip region, respectively
s	function of the Ramberg–Osgood exponent n
$s_0^{a,m}$	entropy of the austenite and martensite phase, respectively
T, T_0	absolute temperature and absolute reference temperature
u_x, u_y	displacement components in the x - and y -directions, respectively
x, y	Cartesian crack tip coordinates
\hat{x}, \hat{y}	normalized Cartesian crack tip coordinates
z	volume fraction of martensite
α	coefficient in the Ramberg–Osgood hardening law
δ	parameter controlling the pressure dependence of the transformation surface
ϵ_{eff}^p	effective plastic strain
ϕ	angular crack tip function
ρ_0	mass density
σ_{eff}	effective stress
$\sigma_{ij}, \tilde{\sigma}_{ij}$	stress tensor components and the normalized counterpart
$\bar{\sigma}_{ij}$	angular dependence of the crack tip stress components from the HRR solution
$\tilde{\sigma}_{ij}$	angular dependence of the crack tip stress components from the linear elastic solution
$\boldsymbol{\tau}$	Kirchhoff stress tensor
ν	Poisson's ratio
$(\cdot):(\cdot)$	tensorial contraction over two indices
$\text{tr}(\cdot)$	tensorial trace
$\text{sym}(\cdot)$	the symmetric part of a tensor
$(\cdot)^{\text{dev}}$	the deviatoric part of a tensor
(\cdot)	material derivative with respect to time
$(\cdot)_i$	isochoric part of a tensor
$(\cdot)^{-1}$	inverse of a tensor

the load transfer to the martensite while larger martensite islands carry more load, and hence are more likely to fracture. Similar observations are made in [17]. In [15], it is noted that substantial enhancement of the fracture toughness seems to occur for intermediate volume fractions of martensite, 30–60%, above which the enhancing effect levels off. At higher volume fractions of martensite, the ductility of the material is found to be severely degraded by the extensive presence of hard martensite [17]. Transformation of austenite into martensite has also been observed in relation to hydrogen embrittlement of dual-phase steel by sensitizing the austenite grain boundaries to hydrogen. Subsequent fracture then progresses along these boundaries [1]. Regarding the appearance of the transformation zones in the vicinity of a crack-tip, it is observed in [2] that the shape of

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