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Side-groove effects in three-dimensional small-scale yielding: A load and thickness-scaling model

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ABSTRACT

This study investigates the influence of side grooves on near-front fields that drive cleavage fracture processes in ferritic steels under 3D small-scale yielding conditions. High-fidelity, finite-strain analyses of boundary-layer models for initially straight crack fronts provide elastic–plastic fields. Numerical solutions demonstrate that non-dimensional, self-similar scaling of crack-front fields for plane-sided specimens also holds for the side-grooved configurations. Furthermore, Weibull stress values exhibit a non-dimensional, thickness scaling controlled by a single non-dimensional parameter. This thickness scaling holds for low-to-high hardening rates typical of ferritic steels under imposed loading levels that range in a 3D setting from near plane-strain to near plane-stress conditions.

1. Introduction

Fracture testing programs on structural metals using laboratory-scale specimens most often employ compact-tension, $C(T)$, or single-edge notch bend, $SE(B)$, geometries. Side grooves prove convenient/necessary to reduce crack-front tunneling during $J-\Delta a$ tests (see ASTM E1820 [1]) and to promote near plane-strain conditions. In ASTM 399 (K_{Ic}) and E1921 (K_{Jc}) tests [2,3], the introduction of side grooves after pre-cracking removes material near the outside surfaces that experiences less fatigue growth thereby effectively straightening the crack front remaining between the side grooves. Side grooves alter significantly the distributions of displacement, strain and stress over the plastically deforming, crack-front material compared to those found in similar plane-sided specimens. Under increased loading and plastic deformation, plane-sided specimens experience an increasingly larger region of diminished, pointwise local J-values and stress levels relative to centerplane values from the influence of the traction-free outside surfaces. This condition leads to significant tunneling in $J-\Delta a$ testing and to reduced volumes of highly-stressed material in K_{Jc} testing to measure the T_0 [3] temperature for ferritic steels in the ductile-to-brittle transition region.

Elastic–plastic solutions for side-grooved specimens remain comparatively sparse, and few studies employ sufficient mesh refinement to resolve both mechanical fields and local J-values near the root of the side groove. Early studies using quite coarse meshes [4,5] reported more uniform stress and deformation variations across the crack front in side-grooved $C(T)$s. Analyses by Nevalainen and Dodds [6] of side-grooved $C(T)$ specimens with increased through-thickness mesh refinement indicated that the highest local J-values develop near the side groove. Side-grooved specimens also retain a more uniform variation of local J-values over the thickness in comparison with plane-sided solutions. Kim et al. [7] analyzed C-shaped, bend specimens with similar (thickness) mesh refinement; they find peak local J-values at the side groove and

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Nomenclature

3D	three-dimensional
DBT	ductile-to-brittle transition
SSY	small-scale yielding
(r,θ,Z)	cylindrical coordinate system with origin at the crack front
(X,Y,Z)	cartesian coordinate system with origin at the crack front
$\overline{K}$	normalized stress intensity factor, i.e., loading level
$\overline{R}$	far-field radius of 3D SSY model
β	T-stress factor: $T = \beta K_I/\sqrt{\pi a}$
Γ	curve in $X-Y$ plane that contains crack front
$\mathcal{C}_{3D}$	3D Weibull stress thickness scaling parameter
μ	elastic shear modulus
ν	Poisson's ratio
ρ_0	initial root radius of crack front
ρ_{SG}	initial root radius of side groove
σ_1	maximum principal stress
σ_w	Weibull stress
σ_0	material yield stress
σ_{th}	threshold stress
σ_u	Weibull stress value with a probability of failure of 63.2 %
$\sigma_{w-\min}$	threshold Weibull stress
B	gross thickness
B_N	notched thickness
E	Young's modulus
J	J-integral applied to far-field boundary, sometimes listed as J^{far} for clarity
J^{loc}	J-integral at thickness location on crack front
K_I	mode I stress intensity factor
m	microstructural parameter used to characterize density of microcracks
n	uniaxial power-law hardening constant
T	T-stress
V_0	normalizing volume for Weibull stress computations
$\mathbf{n}$	normal vector to Γ
$\mathbf{P}$	first Piola-Kirchoff stress

more uniform near-front fields. Shen et al. [8] modeled shallow and deep notch SE(T) specimens containing side grooves and show increases of local J near the side grooves and elevations of stress-based constraint parameters Q and A_2 [9,10].

To better understand and quantify the effects of side grooves on mechanical fields across the crack front in the context of elastic–plastic deformations encountered in K_{Jc} testing, this study employs the 3D small-scale yielding (SSY) framework to perform highly refined analyses of plane-side and side-grooved configurations. Also referred to as the boundary-layer model, other researchers adopt the SSY framework to study 2D (plane-stress, plane-strain) [11,12] conditions and later 3D configurations [13,14,10,15–18]. In both 2D and 3D settings, the crack front plastic zone must remain sufficiently small relative to the in-plane model dimensions and contained within linear-elastic material at peak loading. The 2D SSY model has no natural, physical length-scale – only a deformation-based length-scale such as the plastic zone size and crack-tip opening displacement (both scale with J/σ_0). In the 3D setting, the model thickness B sets a physical length-scale; solutions for different thicknesses of the same material demonstrate a non-dimensional scaling with normalized loading expressed in terms of $\overline{K} = K_I/\sigma_0\sqrt{B}$ and $\overline{T} = T/\sigma_0$, where K_I and T-stress denote the imposed mode-I loading on the remote boundary and σ_0 defines the flow stress. For demonstrations of the non-dimensional scaling in plane-sided configurations, see [13,10] for stationary cracks and [16,18] for extending crack fronts.

Side grooves are introduced here in the 3D SSY framework with a focus on material flow properties representative of ferritic steels tested in the mid-to-low part of the ductile-to-brittle temperature transition range. Extensive refinement over the thickness enables detailed resolution of the root notch geometry of the side groove and corresponding resolution of the mechanical fields including local J-values quite near the side groove. The 3D SSY model with and without side grooves can represent conditions at cleavage fracture in typical sizes of test specimens tested near or below the T_0 transition temperature and in large but comparatively thin structural components (pipelines, plate girders, hulls, etc.) For example, consider a 25 mm thick component of a moderately hardening steel operating in the DBT region with a mean fracture toughness of 100 MPa$\sqrt{\text{m}}$ and a yield stress of 500 MPa. The in-plane plastic zone size of 5–6 mm at fracture in such structures leads to conditions approximated by the 3D SSY framework.

The analyses described here extend the applicability of non-dimensional scaling concepts for 3D crack-front fields developed previously for the plane-sided, 3D SSY configuration to include the effects of side-grooves. Use of the scalar Weibull