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Fracture in multi-phase materials: Why some microstructures are more critical than others

T.W.J. de Geus [a,b,*], R.H.J. Peerlings [b], M.G.D. Geers [b]

[a] Materials innovation institute (M2i), Delft, The Netherlands
[b] Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands

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ABSTRACT

Our goal is to unravel the mechanisms that lead to failure of a ductile two-phase material – that consists of a ductile soft phase and a relatively brittle hard phase. An idealized microstructural model is used to study damage propagation systematically and transparently. The analysis uncovers distinct microstructural features around early voids, whereby regions of the hard phase are aligned with the tensile axis and regions of the soft phase are aligned with the shear directions. These features are consistently found in regions exhibiting damage propagation, whereby the damage remains initiation driven, i.e. voids nucleate independently of each other. Upon localization, damage is controlled on a longer length-scale relying on a critical relative position of 'initiation hot-spots'. The damage rapidly increases in bands of the soft phase wherein several voids are aligned with the shear directions. The relative arrangement of the voids determines whether the microstructure fails early, or at a substantially higher strain. Although much research is needed to refine these findings for real or more realistic microstructures, in particular in three-dimensions, this paper opens a route to a deeper understanding of the ultimate failure of multi-phase materials.

1. Introduction

It is well established that the evolution of damage in ductile multi-phase materials is strongly influenced by local microstructural features such as the spatial distribution of the phases [29,31,41]. Mechanically speaking these materials comprise one or more hard phase(s) reinforcing one or more soft phase(s). In particular clustering of the hard phase is found to promote void nucleation [5,21,22,28,38], while also the more global hard phase volume fraction is found to correlate with the ductility [1,11,26,27,30,36].

Voids generally nucleate throughout the microstructure at all stages of deformation, but only some of them rapidly coalesce into a macroscopic crack at the final stage of deformation [6,20,27,28,32]. Hence, only a small fraction of the nucleated voids actually contribute to the final fracture. The question that thus arises is: what governs the ultimate fracture? Which clusters of voids sufficiently weaken the microstructure to trigger localization? Is the initiation of final fracture predetermined by critical microstructural features? How is this influenced by the relative amount and relative mechanical contrast of the phases? This paper aims to answer these questions using a systematic numerical analysis. An artificial microstructure

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[*] Corresponding author at: Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands.
E-mail addresses: t.w.j.d.geus@tue.nl, tom@geus.me (T.W.J. de Geus).

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Nomenclature

Notation

$\boldsymbol{A}$	second order tensor
a	scalar
$\dot{a}$	rate
Δa	time increment: $a(t+\Delta t)-a(t)$
$\langle a\rangle$	ensemble average
$\bar{a}$	volume average

Symbols

N	number of cells in one volume element
φ	volume fraction (e.g. φ_{hard} is the hard phase volume fraction)
ϕ	fraction
$D\ (\vec{x})$	damage indicator
$\mathcal{I}\ (\vec{x})$	phase (or void) indicator
$\mathcal{P}$	$(\vec{x})$ probability of a certain phase (or void)
$\vec{e}_{\text{x}}, \vec{e}_{\text{y}}$	Cartesian basis vector (in x- and y-direction)
$\vec{x}$	position vector
$\bar{\boldsymbol{\varepsilon}}$	macroscopic logarithmic strain tensor
$\bar{\varepsilon}$	macroscopic effective logarithmic strain
$\bar{\varepsilon}_{\text{v}}$	macroscopic volumetric effective logarithmic strain
$\bar{\varepsilon}_{\text{d}}$	macroscopic deviatoric effective logarithmic strain
$\bar{\varepsilon}_{\text{f}}$	macroscopic equivalent logarithmic strain at which fracture initiation is predicted
$\bar{\tau}_{\text{f}}$	macroscopic equivalent Kirchhoff stress at which fracture initiation is predicted
$\boldsymbol{\varepsilon}_{\text{e}}$	$(\vec{x})$ logarithmic elastic strain tensor
ε_{p}	$(\vec{x})$ effective plastic strain
Φ	$(\vec{x})$ yield function
$\boldsymbol{\tau}$	$(\vec{x})$ Kirchhoff stress tensor
τ_{eq}	$(\vec{x})$ equivalent Kirchhoff stress
τ_{m}	$(\vec{x})$ hydrostatic Kirchhoff stress
$\eta(\vec{x})=\tau_{\text{m}}(\vec{x})/\tau_{\text{eq}}(\vec{x})$	stress triaxiality

Material constants

E	Young's modulus
ν	Poisson's ratio
K	bulk modulus
τ_{y0}	initial Kirchhoff yield stress
H	hardening modulus
$\chi=\tau_{\text{y}}^{\text{hard}}/\tau_{\text{y}}^{\text{soft}}$	phase contrast: ratio of the (current) yield stress of the hard and of the soft phase
ε_{c}	critical effective plastic strain
$A,\ B$	dependence of the critical strain ε_{c} on the stress triaxiality dependency η
ε_{pc}	critical effective plastic strain at infinitely high stress triaxiality

is used in which the two phases are randomly distributed in a regular grid of square cells. Although such microstructures are of course not very realistic, they enable a transparent analysis, in which mechanisms that consistently occur, in a large set of random microstructures, are naturally identified as damage 'hot-spots'. The idealized microstructure also allows us to systematically vary microstructural parameters, without any bias or cross-talk due to experimental limitations. Compared to other studies in the damage propagation regime [e.g. 28,40], this paper adds a statistical perspective. While compared to earlier statistical studies [e.g. 15,24] this paper goes beyond the stage of fracture initiation.

To enable the statistical analysis, the mechanics are modeled in a simple and efficient way. The two phases are treated as isotropic elasto-plastic, and the damage is modeled by a simple indicator. Based on the value of the damage indicator, individual cells are eroded from the microstructure without prior softening. This implies that the cell size is used to regularize the damage. A statistically representative ensemble of random periodic volume elements are considered for which all conditions are identical, and only the microstructural arrangement of the phases differs.

The adopted periodicity does not allow an analysis beyond the loss of stability, in the post-critical regime [31]. Remedies for this are available in the literature [10,17,23]. However, the added computational complexity render them unattractive for the statistical analysis carried out here. Sufficiently large volume elements are therefore used with conventional periodic