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# Microstructural effects on ductile fracture in heterogeneous materials. Part I: Sensitivity analysis with LE-VCFEM

Daniel Paquet, Somnath Ghosh *

*Department of Mechanical Engineering, The Ohio State University, 201 West 19th Avenue, Columbus, OH 43210, United States*

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ABSTRACT

Ductile failure of heterogeneous materials, such as cast aluminum alloys and discretely reinforced aluminums or DRA's, initiates with cracking, fragmentation or interface separation of inclusions, that is followed by propagation in the matrix by a ductile mechanism of void nucleation and growth. Damage localizes in bands of intense plastic deformation between inclusions and coalesces into a macroscopic crack leading to overall failure. Ductile fracture is very sensitive to the local variations of the microstructure morphology. This is the first of a two part paper on the effect of microstructural morphology and properties on the ductile fracture in heterogeneous ductile materials. In this paper the *locally enhanced Voronoi cell finite element method* (LE-VCFEM) for rate-dependent porous elastic–viscoplastic materials is used to investigate the sensitivity of strain to failure to loading rates, microstructural morphology and material properties. A model is also proposed for strain to failure, incorporating the effects of important morphological parameters.



## 1. Introduction

Ductile failure in metals and alloys containing heterogeneities such as particulates, fibers or precipitates, generally initiates at the heterogeneity with fragmentation or interface separation. Subsequently, the microstructural damage propagates into the matrix by mechanisms of void growth. Often, the damage localizes in bands of intense plastic deformation between heterogeneities, which subsequently coalesce into macroscopic cracks leading to complete failure. Experimental studies on ductile failure have shown strong connections between the microstructural morphology and damage nucleation and growth. A robust understanding of the influence of the microstructure on ductile fracture is essential for material design.

A variety of experimental studies have been undertaken on the influence of morphology on ductile failure, particularly related to cast aluminum alloys and DRA's [1–12]. In their studies on cast aluminum alloys, Caceres et al. [13,14,6,15–17] have shown that ductility of the Al–7%Si–0.4%Mg cast alloy depends on both the dendrite cell size and the size and shape of silicon inclusions. While these experimental studies offer good qualitative understanding, they do not quantify the influence of microstructure parameters on ductile fracture. Often, the difficulty arises with isolating the effect of individual morphological parameters like shape, size or spatial distribution [15]. Analytical and computational models have been implemented for fulfilling this need. Computational studies have been conducted to study elastic–plastic deformation and ductile failure of heterogeneous materials in [18–24]. A majority of these are unit cell models with size scales exceeding 1 μm, that use continuum micromechanics for modeling inclusions and matrix [25]. There is a paucity of image-based models that consider aspects of the real microstructural morphology, such as non-uniformities in inclusion shape, size, orientation and spatial distribution. The predictive capability of unit cell models for failure properties is very limited due to

* Corresponding author. Tel.: +1 614 292 2599; fax: +1 614 292 7369.
*E-mail address:* ghosh.5@osu.edu (S. Ghosh).

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**Nomenclature**

| | |
|---|---|
| $a$, $b$ | inclusion major and minor axes |
| $d$ | inclusion size $d = 2\sqrt{ab}$ |
| $\bar{d}$ | inclusion normalized size $\bar{d} = d/L_{MD}$ |
| $\mathbf{e}$ | macroscopic strain tensor |
| $E$ | Young's modulus |
| $f_0$ | initial void volume fraction |
| $L$ | material characteristic length |
| $L_{MD}$ | characteristic length of microstructural domain |
| $m$ | Weibull modulus for crack initiation criterion |
| $N$ | work-hardening exponent |
| $P^{cr}_{frag}$ | critical probability for cracking of inclusions |
| $v_0$ | reference volume for crack initiation criterion |
| $V_f$ | inclusion volume fraction |
| $\alpha$ | inclusion aspect ratio $\alpha = a/b$ |
| $\gamma_0$ | viscosity constant |
| $\boldsymbol{\epsilon}$ | microscopic strain tensor |
| $\epsilon_{fail}$ | strain to failure |
| $\theta$ | inclusion orientation |
| $\iota$ | cluster contour index |
| $\kappa$ | cluster index |
| $v$ | Poisson's ratio |
| $\rho$ | inclusion roundness $\rho = b/a$ |
| $\boldsymbol{\sigma}$ | microscopic stress tensor |
| $\sigma_{max}$ | maximum tensile strength |
| $\sigma_w$ | characteristic strength of inclusions |
| $\sigma_y$ | initial yield stress of the underlying matrix without voids |
| $\sigma_0$ | yield stress of the underlying matrix without voids |
| $\boldsymbol{\Sigma}$ | macroscopic stress tensor |

*Abbreviations*

| | |
|---|---|
| Clus-1 | single cluster hard core |
| Clus-3 | triple cluster hard core |
| DOF | degree of freedom |
| DRA | discretely reinforced aluminum |
| GTN | Gurson–Tvergaard–Needleman |
| HC | hard core |
| LE-VCFEM | locally enhanced Voronoi cell finite element model |
| MAF | mean local area fraction |
| MNND | mean near neighbor distance |
| MPD | minimum permissible distance |
| MPD-CL | cluster minimum permissible distance |
| SDAF | standard deviation of local area fraction |
| SDNND | standard deviation of near neighbor distance |
| SEM | scanning electron microscopy |
| VCFEM | Voronoi cell finite element method |
| #CL | number of clusters |
| #INC | number of inclusions |
| #INC-CL | number of inclusions in cluster |

over-simplification of the microstructure. Quite often, critical local features necessary to model strain to failure are lost in these models. Ductile fracture depends strongly on the extreme values of microstructural characteristics, e.g. nearest neighbor distances, highest local volume/area fraction, etc. and computational models must feature some of these characteristics for accuracy. Additionally, many of the existing studies have focused only on the initial stages of ductile damage, e.g. crack nucleation in the inclusions, and have not considered evolution of ductile failure by matrix void growth and coalescence.

Computational models developed by Ghosh et al. [26–32] have focused on more realistic representation of microstructures with non-uniform dispersion of heterogeneities. The microstructural Voronoi cell finite element model or VCFEM by Ghosh et. al. [26–31] offers significant promise for accurate micromechanical analysis of arbitrary heterogeneous microstructures with high efficiency. Morphological non-uniformities in dispersions, shapes and sizes, obtained from micrographs are readily modeled by this method [33]. This method has been extended in the locally enhanced VCFEM (LE-VCFEM) [32] to