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SIZE EFFECTS IN VOID COALESCENCE

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Summary The importance of the strain gradients that evolves at the onset of void coalescence at micron-scale is demonstrated through a detailed numerical study. Here, a 3D numerical framework is exploited to grain a parametric understanding of the influence of void size and void spacing, and a direct comparison to a recent extension of the coalescence criterion by Thomason is presented. Taking into account the intrinsic length scales inherited by the ductile failure process shows a clear increase in the level of the average volume stress, perpendicular to the plane of localization, at which void coalescence occurs. Oblate voids are particularly affected by the evolving strain gradients. The increase in stress level predicted in a gradient enhanced matrix material are, however, yet to be properly addressed in existing continuum models as both the Thomason criterion, as-well as the Gurson modeling framework, rest on conventional plasticity theory.

INTRODUCTION

The governing mechanics in ductile failure have been subject to intensive studies through decades of research (Tvergaard, 1990; Benzerga and Leblond, 2010), and it has been established that ductile failure generally progress by void nucleation and growth to coalescence at the micron-level. However, existing state-of-the-art micro-mechanics based damage models do not include the experimentally observed intrinsic length scales related to the void size, but instead only account for the void volume fraction (Gurson, 1977) - occasionally in combination with the void shape or a non-local measure of porosity (Gologanu et al., 1997). However, materials that plastically deform by dislocations movement are known to display size effects by elevated stress levels and restricted plastic flow. The general trend in metals is that *smaller is stronger*. Recent research has proven size effects to be important to problems where deformation varies significantly in the micrometer range - the range where the void coalescence process unfolds. Thus, the intrinsic length scale will inevitably influence the ductile failure process.

The present work focuses at the onset of coalescence by adopting the model set-up from Tekoğlu et al. (2012), but here includes a gradient enriched matrix material. The aim is to bring out the effect of the strain gradients that evolves during the interaction between voids at the micron level, and to highlight their implications on existing coalescence models. E.g. a direct comparison to a recent extension of the coalescence criterion by Thomason (1990) (see Eq. 1) is presented. To facilitate this comparison, only void coalescence modes located near the x_1x_3-plane are of interest (see Fig. 1a). The Thomason criterion reads:

$$\frac{\sum_{22}^{c}}{\sigma_0} = (1-\eta\chi^2)\left[\alpha^{Th}\left(\frac{1-\chi}{W\chi}\right) + \beta^{Th}\frac{1}{\sqrt{\chi}}\right] \quad (1)$$

where σ_0 is the conventional yield stress, W is the void aspect ratio, χ the relative void spacing, $\eta = \pi/4$ for a cubic unit cell, and $\alpha^{Th} = 0.0819W - 0.0373$, $\beta^{Th} = 0.0036W^5 - 0.003W^4 - 0.1694W^3 + 0.8499W^2 - 1.6743W + 2.5022$, respectively.

MODELING FRAMEWORK

A full 3D numerical modeling framework based on the Fleck and Willis (2009) strain gradient theory has been purpose build for the study presented. The incremental procedure for this model formulation consists of two successive steps in which "Step 1" determines the plastic strain rate field based on the known stress/strain conditions in the current state, whereas "Step 2" subsequently determines the corresponding incremental displacement solution (see Nielsen and Niordson, 2014, for details). To analyze the onset of void coalescence a small strain/deflection set-up is adopted, and the considered unit cell model is shown in Fig. 1a. The cell consists of a rectangular block of matrix material that surrounds a spheroidal void with aspect ratio, $W = R_2/R_1$ (and $R_1 = R_3$), and a relative void spacing of $\chi = R_1/L_1$. Here, R_i and L_i are the void radii in the three directions and the dimensions of the unit cell, respectively. The boundary and loading conditions on the unit cell are adopted from Tekoğlu et al. (2012) such that the average volume stress components: $\sum_{11}$, $\sum_{22}$, $\sum_{33}$, and $\sum_{12}$ can be controlled through the prescribed macroscopic straining; $E_{ii} = U_i/(2L_i)$ and $E_{12} = U_t/(2L_2)$, where U_i are the normal displacements at the unit cell boundaries and U_t is the shear displacement. In this preliminary study, however, the shear displacement remains zero. All FE calculations are preformed with 20-node 3D elements using reduced Gauss integration $(2 \times 2 \times 2)$ for the displacement field, whereas 8-node 3D elements with corresponding Gauss integration are used for the plastic strain rate field.

As the study concentrate on the onset of void coalescence a limit-load type analysis is in focus and, hence, an attempt is made to mimic an incompressible material by employing a Poisson ratio of $\nu = 0.49$, together with a perfectly plastic response of the matrix material. Thus, upon loading plastic flow will localize and the material response reach a limit load at which the critical volume stress perpendicular to the x_1x_3-plane (the $\sum_{22}^{c}$) is extracted.

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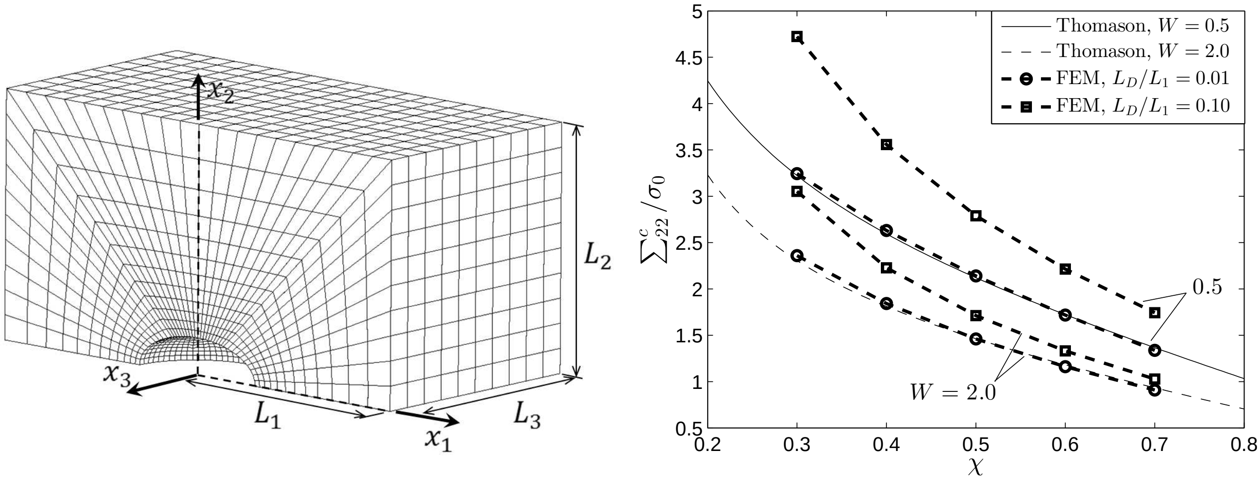

(a) (b)

Figure 1: a) Unit cell model displaying a typical mesh ($W = 0.5$), b) Evolution of $\sum_{22}^{c}$ with the relative void spacing, χ, including results with/without influence of strain gradients ($L_D = 0$ is the conventional limit and reflects J2 flow theory).

RESULTS

The predicted critical volume stress (the $\sum_{22}^{c}$), at which void coalescence takes place, is displayed in Fig. 1b. Here, shown for various void spacings, χ, and two void aspect ratios that correspond to prolate ($W = 2$) and oblate ($W = 0.5$) voids, respectively. First and foremost, a comparison to the Thomason criterion from Eq. (1) reveals accurate predictions in the conventional limit ($L_D/L_1 = 0.01$). But, the strengthening behavior from the plastic strain gradients at micron-scale lift the stress level at which void coalescence occurs - particularly at low relative void spacing. Moreover, it is noticed that oblate voids seem more sensitive to gradient effects as the stress level has increased the most for $W = 0.5$.

CONCLUSION

The present study of the intrinsic length scale effects, related to void coalescence, displays an increased level of the critical stress at which localization of plastic flow occurs between micro-voids. The effect originates from the strengthening behavior predicted for gradient enhanced materials, and one might want to think its implications into a stress based coalescence criterion such as that of Thomason. To fully exploit the findings of the present study, however, new development to the Gurson modeling framework is required. As it sits, this classical micro-mechanics based damage model omits any gradient effects and, hence, cannot accurately represent the stresses over the multiple scales involved in the ductile failure process.

ACKNOWLEDGEMENT

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