# VOID SIZE, SHAPE, AND ORIENTATION EFFECTS UNDER INTENSE SHEARING ACROSS SCALES

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## Abstract

The present work demonstrates how gradient strengthening at the micron scale affects the macroscopic strain at coalescence under intense shearing conditions. The coalescence mechanism relies on severe flattening, rotation, and elongation of the voids causing severe heterogeneous plastic strain to develop near the voids and in the ligament between voids. These gradients are associated with geometrically necessary dislocations, causing a delay in the coalescence process.

## 1. Introduction

The mechanics controlling void coalescence in shear is very different from the well-known hydrostatic tensile-driven void growth to the coealescnece process. Tvergaard [1] demonstrates that microvoids subject to intense shear flatten while they rotate and undergo substantial elongation before interacting with neighboring voids. The mechanism introduces severe plastic straining of the matrix, and plastic flow localizes close to the tips of the flattened void as well as in the ligament between neighboring voids (see also [3]). The plastic strain distribution is highly heterogeneous, and the associated plastic strain gradients are expected to give additional strengthening at the micron scale, affecting both the flattening, the elongation, and the interaction of the neighboring voids. The studies by Tvergaard [1, 2] motivate the present work in quantifying the size-dependent coalescence mechanism of spheroidal voids (ranging from oblate to prolate) under shear-dominated loading conditions. A plane strain unit cell model containing an elliptical void, following Tvergaard [1, 2], is taken as a starting point, while the matrix is modelled with a gradient-enriched material governed by the Fleck and Willis [3] plasticity theory. The gradient plasticity theory introduces an intrinsic material length parameter, $L_D$, which controls the gradient strengthening. . In this way, increasing the length parameters while keeping the void volume fraction and relative intervoid distance constant corresponds to diminishing the material microstructure.

## 2. Results

A finite element unit cell model that represents a periodic array of spheroidal voids (see Fig. 1a-d) facilitates a comprehensive numerical analysis of the void size, shape, and orientation effects under intense shearing conditions. By accounting for finite strains, as well as self-surface contact (for the void surfaces), severe shear deformation of the voids allows reaching coalescence. Figure 1e-f show the deformed void shape at coalescence for a loading case of combined tension and intense shear with $\Sigma_{22}/\Sigma_{12} = 0.6$ . Here, results are shown for two distinct void shapes, $S = [0.5, 2]$, oriented at $\theta = 0°$ in the undeformed state. It is obvious that the intensity of plastic straining smears out for increasing gradient strengthening (increasing $L_D$), which in turn leads to a delay in void coalescence. Moreover, for increasing length parameter, the oblate voids are found to elongate less before coalescence sets while they rotation slightly in the opposite direction to the applied shear loading (see Fig. 1e-f).

The main findings are:

a. The initial void orientation plays a fundamental role in the void deformation mechanism that unfolds prior to localization and void coalescence. The known mechanism for spherical voids that flatten, rotate, and elongates in a shear field is complicated by the void shape (also shown in [2]) and further by the different initial orientations. The results demonstrate how intermediate orientations of the voids can enhance ductility as well as resulting in substantial void deformation and rotation prior to the flattening.

b. The initial relative void size and initial void orientation strongly affect the material ductility across the scales. Common to all configurations is that the ductility increases when down-scaling the microstructure such that the gradient strengthening increases due to large densities of geometrically necessary dislocations needed to accommodate the plastic strain gradients related to the void deformation. The present study also shows that the sensitivity to the void shape diminishes for increasing gradient strengthening, particularly for initial void orientations in the interval $\theta \in [0,67.5]^\circ$.

c. A roughly linear relation between the average shear angle at void coalescence and the material length parameter is found for a wide range of initial void shapes and orientations. The linear fit is best for prolate and slightly oblate voids, whereas the shift in the deformation mechanism for initially oblate voids gives rise to an increasing dependence on the intrinsic material length parameter.

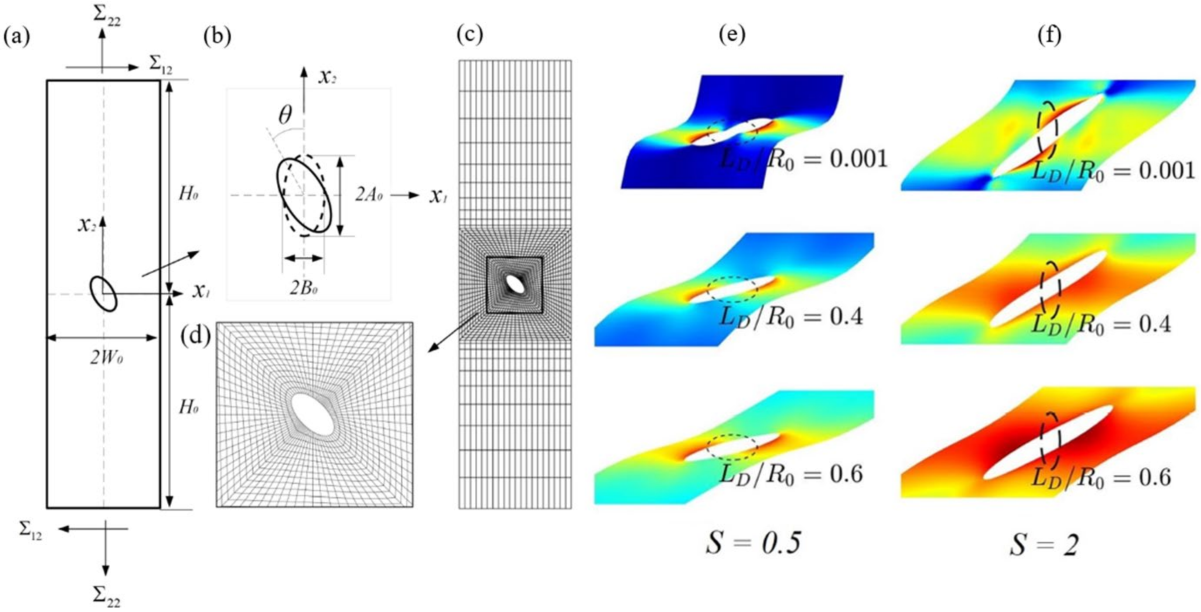

Fig.1 – (a)-(b) A unit cell representation of a periodic array of ellipsoidal voids with initial size, $R_0/W_0$, shape, $S = A_0/B_0$, and initial orientation, $\theta$, measured from the $x_2$-axis. The characteristic void radius is $R_0 = \sqrt{A_0 B_0}$, and the domain aspect ratio is $H_0/W_0 = 4$. (c)-(d) Shows a representative finite element mesh. (e)-(f) Shows the deformed unit cells at coalescence with an overlaid intensity of the plastic straining for two initial voids shapes, $S = [0.5,2]$, with initial orientation $\theta = 0^\circ$ for $\Sigma_{22}/\Sigma_{12} = 0.6$.

## 3. Conclusions

Gradient strengthening delays void coalescence in shear, and the effect is particularly dependent on the initial void orientation. This dependence ties to the deformation mechanisms and the associated plastic straining, which changes depending on how the void's major/minor axis is located relative to the loading.

## Acknowledgements

The work is financially supported partly by the Danish Council for Independent Research in the project "Advanced Damage Models with InTrinsic Size Effects", grant DFF-7017-00121, and the project "Why, Where and When Metals Fail (Triple-W)", grant DFF-0136-00194B.

## References

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