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The role of tension-compression asymmetry of the plastic flow on ductility and damage accumulation of porous polycrystals

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Abstract

The influence of the tension-compression asymmetry of the plastic flow, due to intrinsic single-crystal deformation mechanisms, on porosity evolution and the overall ductility of voided metallic polycrystals is assessed. To this end, detailed micromechanical finite-element analyses of three-dimensional unit cells containing a single initially spherical cavity are carried out. The plastic flow of the matrix (fully-dense material) is described by a criterion that accounts for strength-differential effects induced by deformation twinning of the constituent grains of the metallic polycrystalline materials. The dilatational response of porous polycrystals are calculated for macroscopic axisymmetric tensile loadings corresponding to a fixed value of the stress triaxiality and the two possible values of the Lode parameter. It is shown that damage accumulation, and ultimately ductility of the porous polycrystals are markedly different as compared to the case when the matrix is governed by von Mises criterion. Most importantly, a direct correlation is established between the macroscopic material parameter k that is intimately related to the particularities of the plastic flow of the matrix and the rate of damage accumulation.

Keywords: Twinning; porous polycrystals; porosity evolution; ductility.

1. Introduction

Beginning with the studies of Needleman [10], Gurson [6], Tvergaard [12], Koplik and Needleman [8], micromechanical finite-element (FE) analyses of unit cells have been used to gain understanding of the mechanical response of porous solids. In all these FE studies, it was assumed that the plastic flow of the metallic matrix (void-free material) is governed by the von Mises criterion. However, early on it was recognized that the plastic flow of certain fully-dense, isotropic FCC and BCC polycrystalline materials is not governed by the von Mises criterion (e.g., Drucker, Prager and Hodge, Lenhart, Billington [1-3]).

In this work a FE study is conducted in order to investigate how the tension-compression asymmetry of the plastic flow, which is due to intrinsic single-crystal plastic deformation mechanisms (e.g., twinning), affects the porosity evolution, and ultimately the ductility of isotropic porous polycrystals. It is assumed that the porous polycrystal is well described by a 3D periodic array of initially spherical voids surrounded by a fully-dense elastic/plastic matrix.

The plastic behaviour of the matrix is considered to be governed by the isotropic form of Cazacu *et al.* [4] yield criterion and isotropic hardening. The reasons for adopting this criterion are: (1) although it is pressure-insensitive, it accounts for difference in plastic response between tension and compression; (2) it depends on all principal values of the stress deviator,

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hence it is dependent on the third-invariant of the stress deviator; (3) all the model parameters have a clear physical meaning, namely the criterion involves the uniaxial yield stress in tension, and a scalar material parameter, *k*, which is intimately related to specific single-crystal plastic deformation mechanisms [2].

2. Problem Formulation

2.1. Isotropic form of Cazacu et al. yield criterion

The isotropic form of Cazacu *et al.* [4] yield criterion (CPB06) is:

$$\sqrt{\frac{9}{2\left(3k^2-2k+3\right)}\sum_{i=1}^{3}\left(\left|\sigma_i'\right|-k\sigma_i'\right)^2}=\mathrm{Y_T} \qquad (1)$$

where σ_i' and $i = 1.3$ are the principal values of the deviator of the Cauchy stress tensor σ and Y_T is the yield stress in uniaxial tension. The material parameter k is related with the tension-compression asymmetry of the plastic flow (or with the ratio Y_T/Y_C, i.e., the ratio between the yield stresses in uniaxial tension and uniaxial compression – more details on [4]).
In the present study, three different materials are investigated, which are characterized by:

- $k = 0$ (or Y_T/Y_C=1) which corresponds to a von Mises material (see Eq. (1));
- $k = -0.30$ (or Y_T/Y_C=0.83), which corresponds to a fully-dense isotropic FCC polycrystal that deforms at single-crystal level only by deformation twinning, in agreement with Hosford and Allen [7];
- $k = +0.30$ (or Y_T/Y_C=1.21), which corresponds to a fully-dense isotropic BCC polycrystal, for which the constituent grains are considered to deform only by deformation twinning.

So, if deformation twinning contributes to plastic deformation at single crystal level, the polycrystal displays strength differential effects and thus $k \neq 0$. According to the criterion (Eq. (1)), for $k \neq 0$ the plastic response depends on the sign and ordering of all principal values of σ', or alternatively on both invariants of the stress deviator.

2.2. Unit FE cell model

Full three-dimensional unit cell model computations are conducted. It is assumed that the porous polycrystal contains a regular array of initially spherical voids. The inter-void spacing is considered to be the same in any direction, and thus the unit cell is initially cubic with side lengths $2C_0$ and contains a single void of radius r_0 at its centre. Initial void porosity is f_0=0.0104. FE mesh of the unit FE cell is shown in Fig. 1.

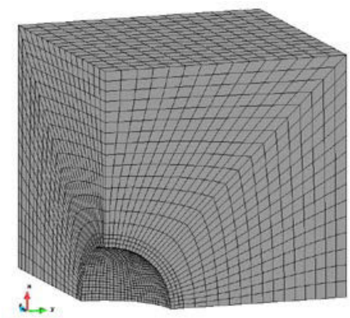

Fig. 1. The finite-element mesh of the unit cell with a spherical void at its centre. Due to material and geometrical symmetries, only one-eighth of the entire unit cell was modelled. The FE mesh contains 12150 8-node hexahedral finite elements and 13699 nodes.

The boundary value problem is posed such that both symmetry conditions and interactions between neighbouring voids are correctly considered. For more details about the boundary value problem of the unit FE cell the reader is referred to [1].
The macroscopic stress state imposed to the unit cell is such that the principal values of the macroscopic Cauchy stresses, Σ_1, Σ_2 and Σ_3, follow an axisymmetric stress path, i.e. $\Sigma_1 = \Sigma_2$, and a loading history such that the stress triaxiality T_Σ and Lode parameter μ_Σ are constant over the entire deformation process.
The response of the porous polycrystal is fully characterized by the isotropic invariants of the macroscopic stress tensor $\mathbf{\Sigma}$, i.e.:

$$\Sigma_m=\tfrac{1}{3}\left(\Sigma_1+\Sigma_2+\Sigma_3\right) \qquad (2)$$

$$\Sigma_e=\sqrt{3\mathrm{J}_2}=\sqrt{\tfrac{3}{2}\left(\Sigma_1'^2+\Sigma_2'^2+\Sigma_3'^2\right)} \qquad (3)$$

$$\mathrm{J}_3^\Sigma=\Sigma_1'\,\Sigma_2'\,\Sigma_3' \qquad (4)$$

$$\mathrm{E_e}=\sqrt{\tfrac{2}{3}\left(\varepsilon_1^2+\varepsilon_2^2+\varepsilon_3^2\right)} \qquad (5)$$

The definitions for the stress triaxiality and Lode parameter are, respectively:

$$\mathrm{T}_\Sigma=\Sigma_m/\Sigma_e \qquad (6)$$

$$\mu_\Sigma=\frac{3\sqrt{3}}{2}\frac{\mathrm{J}_3^\Sigma}{\left(\mathrm{J}_2^\Sigma\right)^{3/2}} \qquad (7)$$

The finite-element analyses were performed with DD3IMP [9,11], an in-house quasi-static elastoplastic code with a fully-implicit time integration scheme. The initial FE mesh of one-eighth of the unit cubic cell contains 12150 elements (8-node hexahedral finite elements; selective reduced integration technique, with 8 and 1 Gauss points for the deviatoric and volumetric parts of the velocity field gradient, respectively) and a total of 13699 nodes. A mesh refinement study was done to ensure that the results are mesh-independent; more details about the FE model can be found on [1].
In the numerical simulations only the tension-compression (σ_T/σ_C) asymmetry parameter, i.e., *k,* was changed. All other input material parameters are kept, i.e., the elastic properties (E= 200 GPa, ν= 0.33, Young modulus and Poisson ratio) and the material parameters (Y_0=400 MPa, A/Y_0=7.82 and n=0.10) involved in the isotropic hardening law describing the evolution of the matrix tensile yield strength with local equivalent plastic strain,

$$Y_T = A\left(\varepsilon_0 + \bar{\varepsilon}^p\right)^n, \text{ with } Y_0 = A\varepsilon_0^n \qquad (8)$$

2.3. Loading cases

In the present study, the following macroscopic axisymmetric loading cases will be analysed and discussed. The first one corresponds to the well-known equibiaxial tensile stress state (EBT), a loading of great practical importance in metal forming. For EBT are:

a) T_Σ=+2/3 and μ_Σ=−1,
   i.e. Σ_1/Σ_2=1 and Σ_3=0.

The second loading corresponds to the same stress triaxiality but positive Lode parameter, namely:

b) T_Σ= +2/3 and μ_Σ=+1,
   i.e. Σ_1/Σ_2=1 and Σ_3/Σ_1=4.

The macroscopic stress tensors have the following form (α is a loading parameter), respectively:

$$\boldsymbol{\Sigma}^{a)} = \alpha\begin{bmatrix}1 & & \\ & 1 & \\ & & 0\end{bmatrix}, \quad \boldsymbol{\Sigma}^{b)} = \alpha\begin{bmatrix}0.25 & & \\ & 0.25 & \\ & & 1\end{bmatrix} \qquad (9)$$

3. Numerical Results

Results concerning the macroscopic stress-strain response and damage evolution (or evolution of the void volume fraction) with the equivalent strain are shown in Figs. 2 and 3 in case of equibiaxial loading (T_Σ=+2/3 and μ_Σ=−1), and in Figs. 4 and 5 in case of the loading with the same stress triaxiality but positive Lode parameter, i.e. T_Σ=+2/3 and μ_Σ=+1.
On Figs. 2-5, black and white dots mark the onset of void coalescence and failure, respectively, for the cases where such events took place. The most interesting and important aspect to be highlighted from these results is how the specificities of the plastic flow of the matrix affect every aspect of the mechanical response of the porous solid.

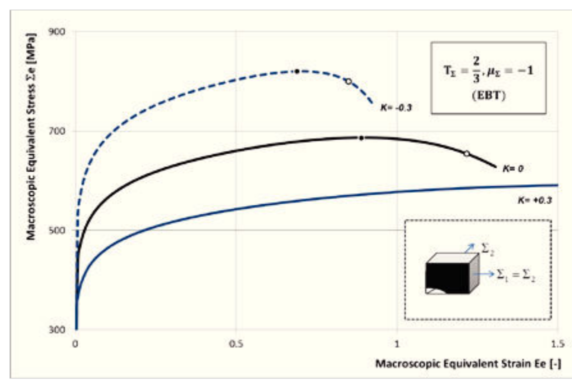

Fig. 2. Comparison between the macroscopic stress-strain response for materials with matrix characterized by different tension compression asymmetry ratios: k=-0.3, Mises (k=0) and k=+0.3, obtained by cell calculations for an equibiaxial tensile loading, T_Σ=+2/3 and μ_Σ=−1.

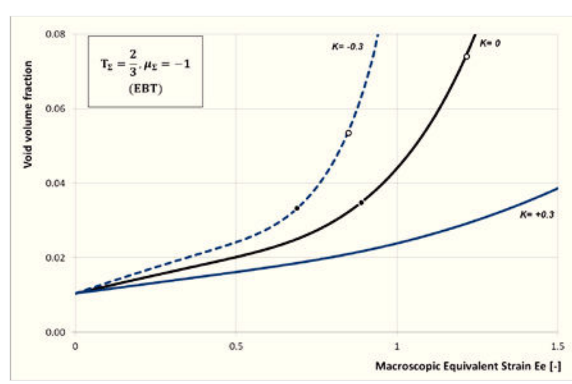

Fig. 3. Evolution of the void volume fraction with the macroscopic equivalent strain Ee, obtained by cell calculations for materials with matrix characterized by different asymmetry ratios: k=-0.3, Mises (k=0) and k=+0.3, for an equibiaxial tensile loading, T_Σ=+2/3 and μ_Σ=−1.

In particular, Figs. 3 and 5 clearly show a strong coupling between the sign of Lode parameter, i.e., the effect of J_3, and the ductility and damage accumulation on materials exhibiting different tension-compression asymmetries.

Note that under EBT (i.e., $\mu_\Sigma=-1$), the FCC polycrystal, which is characterized by k=-0.3, exhibits a much faster void growth than the other materials, while in case of the BCC polycrystal, characterized by k=+0.30, the rate of void growth is the slowest, and thus a much larger ductility can be attained. Remark that the opposite behaviour is observable in case of a loading with the same macroscopic stress triaxiality but positive Lode parameter ($\mu_\Sigma=+1$).

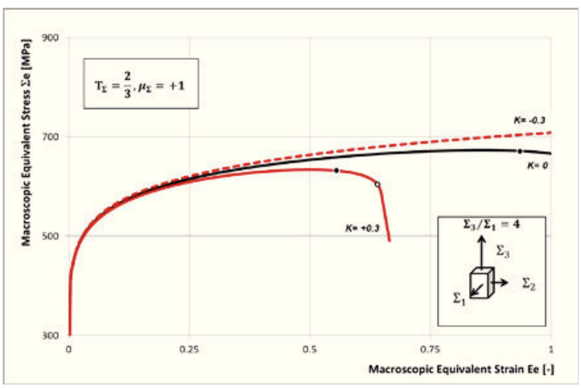

Fig. 4. Comparison between the macroscopic stress-strain response for materials with matrix characterized by different σ_T/σ_C asymmetry ratios: k=-0.3, Mises (k=0) and k=+0.3, obtained by cell calculations for a macroscopic loading characterized by $T_\Sigma=+2/3$ and $\mu_\Sigma=+1$.

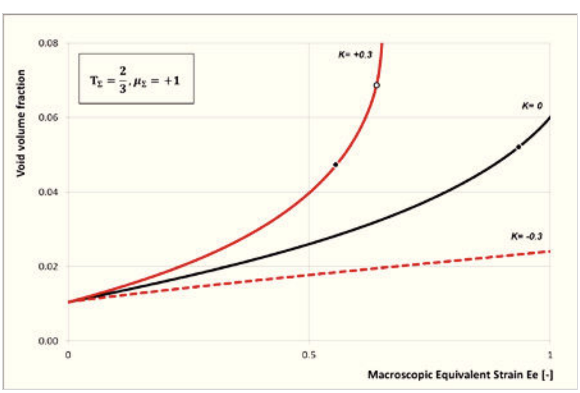

Fig. 5. Evolution of the void volume fraction with the macroscopic equivalent strain Ee, obtained by cell calculations for materials with matrix characterized by different σ_T/σ_C asymmetry ratios: k=-0.3, Mises (k=0) and k=+0.3, for a macroscopic loading characterized by $T_\Sigma=+2/3$ and $\mu_\Sigma=+1$.

In this case (see Fig. 5), the fastest void growth occurs for the BCC polycrystal (k=+0.30) and the slowest in case of the material with (k=-0.30). These results are well correlated with the softening observable in macroscopic stress strain responses, namely on the FCC polycrystal (k=-0.30) in Fig. 3 and the BCC polycrystal (k=+0.30) in Fig. 5, in which softening, the onset of void coalescence and failure are totally correlated with porosity evolution.

The Mises material exhibits always an intermediate behaviour whatever the loading (see also [2,3] for examples of other loading scenarios).

4. Conclusions

The effect of the tension-compression asymmetry in plastic flow, due to intrinsic single-crystal deformation mechanisms such as twinning, on porosity evolution and on the overall ductility of voided polycrystals was assessed by FE cell calculations.

It was clearly shown that the tension-compression asymmetry in the plastic flow of the polycrystals, described by the parameter *k* of the Cazacu *et al.* criterion [4], has a very strong influence on all aspects of the mechanical response of the porous metallic polycrystals. At a fixed value of the stress triaxiality T=+2/3, a strong coupling between tension-compression asymmetry of voided polycrystals and Lode parameter (or the sign of the third invariant of the stress deviator) of the applied stress was observed. Moreover, from previous works the same conclusion holds true for any other value of the stress triaxiality (see more details on [2,3]). These results point out that optimum ductility cannot be obtained without combining the material properties with the deformation process. Furthermore, the initial microstructure of a material can be "tailored" such as to perform better for a given deformation process.

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References

[1] J.L. Alves, B. Revil-Baudard, O. Cazacu, Modell. Simul. Mater. Sci. Eng. 22(2) (2014) 025005.

[2] J.L. Alves, O. Cazacu, Eur. J. Mech. - A/Solids 51 (2015) 44.

[3] J.L. Alves, O. Cazacu, C. R. Mec. 343(2) (2015) 107.
[4] O. Cazacu, B. Plunkett, F. Barlat, Int. J. Plast. 22 (2006) 1171.
[5] O. Cazacu, N. Chandola, J.L. Alves, B. Revil-Baudard, Eur. J. Mech. - A/Solids 47, 194 (2014).
[6] A.L. Gurson, J. Eng. Mater. Technol. 99 (1977) 2.
[7] W.F. Hosford, T.J. Allen, Metall. Trans. 4 (1973) 1424.
[8] J. Koplik, A. Needleman, Int. J. Solids Struct. 24(8) (1988) 835.
[9] L.F. Menezes, D.M. Neto, M.C. Oliveira, J.L.Alves, Proceedings of ESAFORM2011 - 14th International Conference on Material Forming, Queen's University Belfast, Ireland, April 27-29, 2011, pp. 1220-1225.
[10] A. Needleman, J. Appl. Mech. 39 (1972) 964.
[11] D.M. Neto, M.C. Oliveira, L.F. Menezes, J.L. Alves, Comput. Methods Appl. Mech. Eng. 271 (2014) 296.
[12] V. Tvergaard, Int. J. Fract. 17 (1981) 389.