How much input is nedded from the microstructure to model ductile fracture?

Amine A. Benzerga, Jacques Besson, André Pineau

HOW MUCH INPUT IS NEEDED FROM THE MICROSTRUCTURE TO MODEL DUCTILE FRACTURE?

A. A. Benzerga[1], J. Besson[2] and A. Pineau[2]
[1] Aerospace Engineering Department, Texas A&M University, TAMU 3140, College Station TX 77843, USA
[2] Ecole des Mines de Paris, Centre des Matériaux, UMR CNRS 7633, BP 87, F91003 Evry Cedex

ABSTRACT

New phenomena of ductile behavior are briefly presented that are mostly relevant for anisotropic materials. These include void rotation induced ductility enhancement under off-axes loading and two modes of coalescence that are different from the internal necking mode. The effects associated with some phenomena are of first order and the general question arises as to what microstructural parameters affect ductile behavior.

1 INTRODUCTION

Ductile fracture of many alloys involves the nucleation at second phase particles of voids that grow to coalescence. In the local approach to fracture [1, 2], the emphasis is put on micromechanistic failure criteria that explicitly involve microstructural variables. For given matrix, particle and interface rheological properties, void nucleation depends on particle aspect ratio [3] and particle size as well. Void growth and coalescence involve other variables such as porosity [4, 5], which is related to the volume fraction of void-nucleating particles [6]; other known effects include that of the inclusion shape [7] and, in a more subtle way, the inclusion relative spacing [8, 9].

Most microstructural effects result in an essentially anisotropic ductile behavior. Mathematical modeling of anisotropic behavior has recently been applied to predict failure in round notched steel bars [10] based on cumulated contributions in the field [11]-[14]. The main outcome of using the constitutive equations developed in [10] is a loading response that includes the transition from a pre-coalescence state to a “cracked” state without using adjustable factors. In addition, the effects of porosity, void aspect ratio and void relative spacing all appear as first-order effects on ductility. In [15] quantitative metallography was used to determine the initial values of those variables.

The aim of this study is to question, on purely experimental grounds, whether a theory that includes the aforementioned effects of void volume fraction, aspect ratio and relative spacing is a complete (or sufficient) theory. New damage micromechanisms are highlighted which may affect ductility. In particular, the emphasis is put on (i) the evolution of void orientation; (ii) modes of void coalescence other than the internal necking mode and (iii) void nucleation at tiny particles. In each case, the appropriate variables are identified and the macroscopic effects clearly correlated.

2 MATERIAL

The material is a medium carbon low alloy steel with a ferrite-pearlite microstructure cut from a 10mm-thick hot-rolled plate [15, 16]. Tensile plane strain specimens as well as round notched bars were machined at different orientations in the rolling plane L–T. With ψ_0 indicating the loading orientation measured from the rolling orientation, L, three orientations were investigated: $\psi_0 = 0°$, $\psi_0 = 45°$ and $\psi_0 = 90°$. The latter corresponds to transverse loading along T. The through-thickness orientation is denoted by S. The bars were deformed at room temperature at low strain rate (10^{-4} to $10^{-3}\mathrm{s}^{-1}$) using a closed-loop servohydraulic MTS test machine so that the tests could be interrupted at any deformation level. A large number of specimens were sectioned in either longitudinal or transverse planes, mechanically polished up to 0.25μm and then observed using optical and scanning electron microscopy. The second-phase particles of interest here are the elongated MnS inclusions, which are preferentially oriented along the L direction.

3 RESULTS

3.1 Void rotation

Long voids are nucleated at the location of MnS inclusions. The void orientation is found to evolve in the course of plastic deformation and this occurs under off-axes loading ($\psi_0 = 45°$) as well as in loading along a principal direction (L or T). Figure 1(a) shows a rotated elongated cavity under longitudinal loading ($\psi_0 = 0°$) of a notched bar. The maximum rotation over all specimens was measured to be less than 20°. Void rotation under L-loading is favored at low stress triaxiality and near a free surface (see sketch) where significant changes in the eigenstrain directions occur. Thus, this type of rotation is a material rotation and can be modeled in a straightforward way [10]. Even though this material-driven void rotation increases the susceptibility to void growth, it is, however, localized far from the crack initiation site and hence does not affect much ductility.

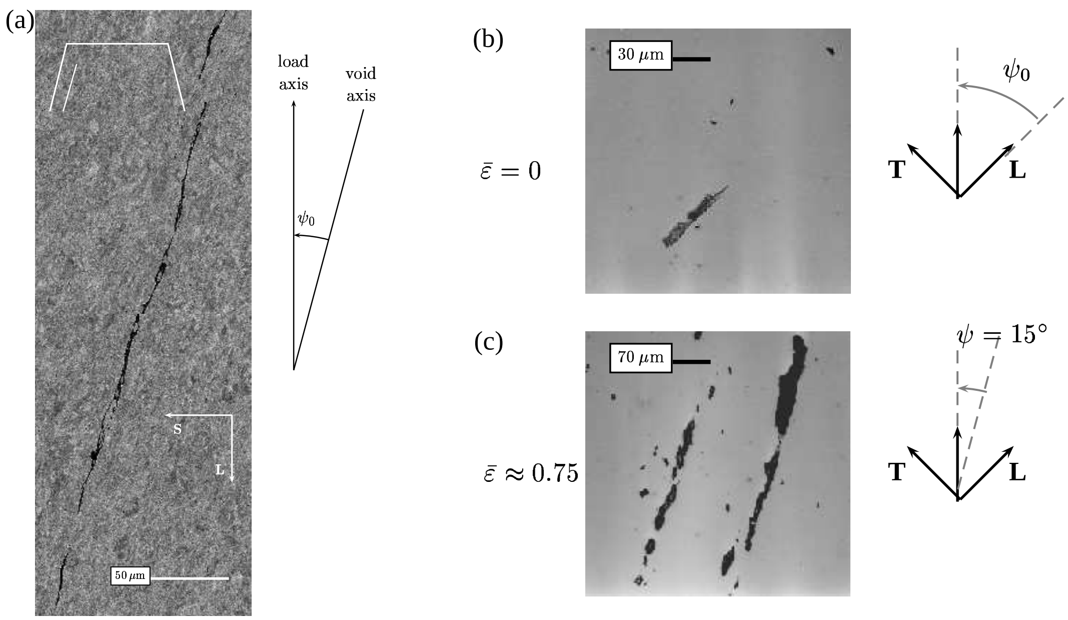

Figure 1: Void rotation (a) in longitudinal loading ($\psi_0 = 0°$), (b) and (c) in off-axes loading ($\psi_0 = 45°$). Sketch at the top in (a) indicates location of cavity near free surface of broken notched bar.

On the other hand, a significant re-alignment of elongated voids is observed under off-axes loading. Figure 1(c) shows a set of long voids oriented at $\psi \approx 15°$ from the loading axis in a highly deformed region, which is located in the minimal section of a notched bar. Upon nucleation, such voids were oriented at $\psi_0 = 45°$ as indicated by the orientation of a reference MnS inclusion prior to deformation (Fig. 1(b)). This indicates a rotation of about 30°. Etching using a 2% Nital solution made it possible to separate out this void re-alignment from material induced rotation. Etching revealed indeed a banded microstructure with well distinguished pearlite bands that extended symmetrically about the minimal section. The orientation of the pearlite bands, which qualitatively indicates the material rotation, did not correlate with the orientation of the void population.

As seen in Fig. 2 the macroscopic effect of void rotation on ductility under off-axes loading is remarkable. Ductility is here measured by the average strain to failure initiation, $\bar{\varepsilon}_c$. Each point in Fig. 2(b) corresponds to at least three measurements. The particle projected area normal to the load increases with increasing the loading angle, ψ_0. Thus, to first order with triaxial effects disregarded, ductility is expected to steadily decrease with increasing ψ_0. This is opposite to what is seen in Fig. 2(b) both for plane strain and for axisymmetric deformation of a round bar with a mild notch (indicated by $\zeta = 10$). Instead, ductility rather slightly increases in the range 0° to 45° for the angle ψ_0. This behavior is associated with void alignment along the loading direction as shown above.

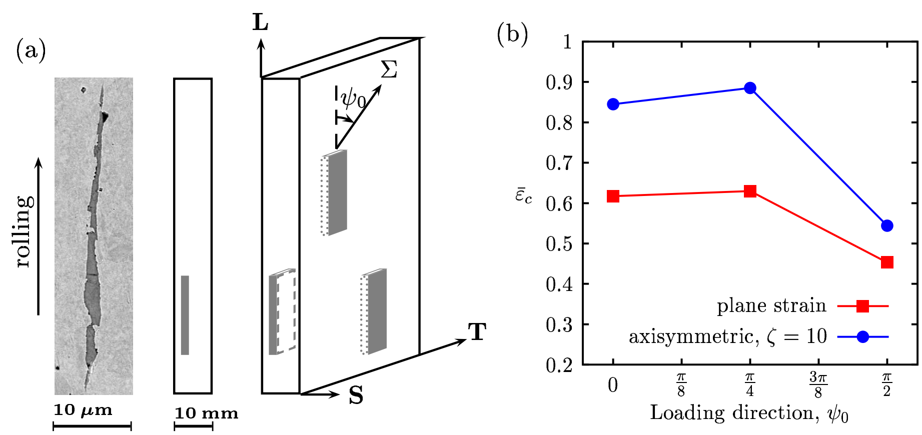

Figure 2: (a) MnS inclusion viewed in L-S and L-T planes. (b) Strain to failure versus loading orientation in L-T plane, ψ_0.

3.2 Void-sheet coalescence

Ductility is most often limited by void-coalescence induced crack initiation. Internal necking is the most common mode for coalescence. One other mode is the so-called void-sheet coalescence. It is still unclear to what extent void-sheet coalescence effectively leads to crack initiation. In particular, the famous illustration due to Cox and Low [17] corresponds to an isolated situation within their tested specimen. Figure 3 shows a case of void-sheet coalescence leading to crack initiation at the center of a notched bar under off-axes loading ($\psi_0 = 45°$). Coalescence here involves two elongated cavities linked through an inclined sheet of much smaller voids. Void-sheet coalescence was consistently observed in most bars with shallow notches for $\psi_0 = 45°$ but not for loading along a principal direction ($\psi_0 = 0°$ or $\psi_0 = 90°$). It is likely that the continuous change in orientation of the void population increases the propensity to void-sheet coalescence by spanning suitable "paths" for void-sheeting. It is, however, the interplay between the positive effect of void rotation and the negative effect of void-sheeting that ultimately governs ductility under off-axes loading conditions.

3.3 Necklace coalescence

Under longitudinal loading ($\psi_0 = 0°$) and sufficiently low stress triaxiality, void growth is predominantly extensional, that is long cavities elongate further. Figure 4(a) shows that coalescence may

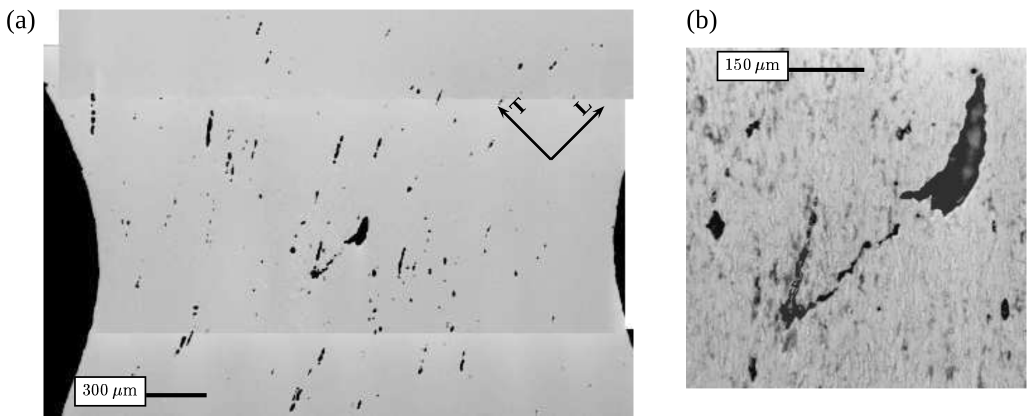

Figure 3: (a) Crack initiation in off-axes loading ($\psi_0 = 45°$) due to (b) void-sheet coalescence.

occur between such cavities along their major axis thus leading to a void that is longer than 300μm. This mode of coalescence is called here *necklace coalescence* and is different from coalescence by internal necking. This mode of coalescence was first seen in numerical simulations [18] for initially spherical voids under triaxial loading with a major radial stress. Here coalescence occurs under a major axial stress and this is due to the large initial void aspect ratio.

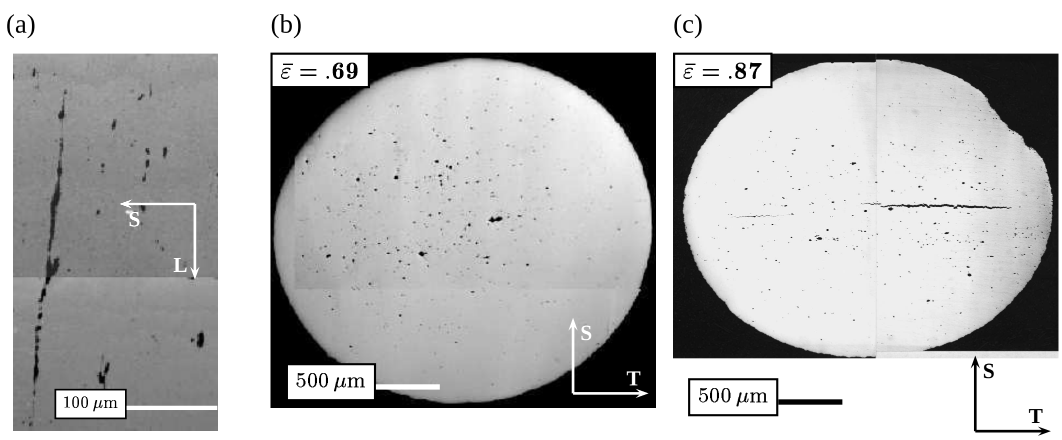

Figure 4: (a) Necklace coalescence under plane strain longitudinal loading. (b) & (c) Cross sections of round notched bars beneath fracture surface for two pipeline steels: (b) steel with no delamination; (c) steel with delamination. Loading is longitudinal in all.

Necklace coalescence is a priori harmless within the range of stress triaxiality encountered here because the increase in void elongation makes the void less prone to radial growth. In a cross-section normal to the loading direction (Fig. 4(b)) long voids are viewed end-on and appear to be isolated from each other. However, under similar circumstances where internal necking along the transverse direction, T, is also possible, necklace coalescence becomes detrimental as it is a driving mechanism for steel delamination (Fig. 4(c)). The micrographs in Figs. 4(b) and (c) were made possible by polishing beneath the fracture surface. Presumably both the void spacing in the T direction and the

3D non-axisymmetric void shape enter into play in determining whether delamination occurs in a given specimen. In particular, in this type of steel, inclusions are often more closely spaced in the T direction. In the steel with delamination, it is likely that the void spacing in the T direction was much smaller than in the steel of this study.

3.4 Void nucleation at sub-micron scale

The particle size distribution spans a wide spectrum that ranges from nano-meter (e.g. carbides) to micron (oxides and MnS). The effect of particles that are much smaller than 1μm is usually neglected although tiny voids are often invoked in void-sheet coalescence. Our repeated observations of (i) cementite particles, (ii) Niobium carbides and (iii) tiny MnS particles located in highly strained regions suggest that there exists a threshold in particle size below which void nucleation is essentially precluded. An example is shown in Fig. 5(a) for a 300 nm diameter particle located less than 100μm ahead of a blunted crack tip (not shown). Voids are nucleated at the poles but do not grow. Figure 5(b) depicts two MnS inclusions viewed end-on (their length is perpendicular to the figure). The estimated local strain is about 0.3. Clearly, the largest particle has fractured, but no void growth occurred, whereas the thinner particle did not break at all. By way of contrast, for geometrically similar but larger MnS inclusions, voids are nucleated at strains of a few percent (Fig. 5(c)).

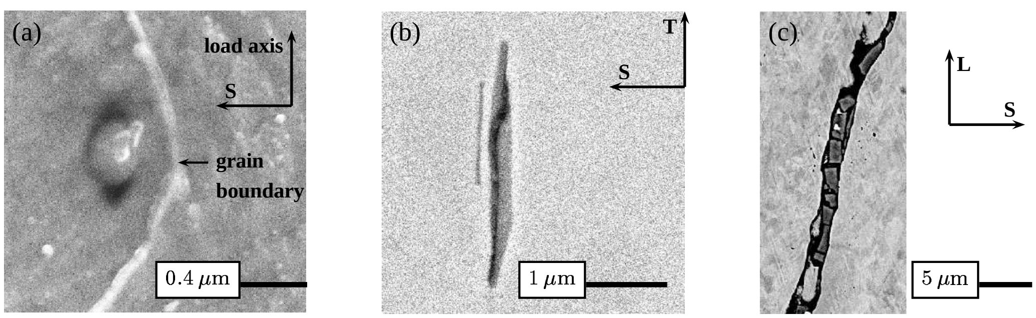

Figure 5: Void nucleation at small scale (a) by decohesion at the poles of a tiny MnS inclusion; (b) by inclusion fracture but no void growth ($\bar{\varepsilon} \approx 0.3$); note thinner unfractured inclusion. (c) Void nucleation at a larger inclusion by fragmentation then decohesion.

4 CONCLUSIONS

The local approach to ductile fracture is being improved thanks to incorporating an enriched description of the initial and evolving microstructure into micromechanics models. While this increases the predictive capability of the approach, challenges remain open for modeling. In this paper highlights were given in relation to void rotation and coalescence modes. (a) The ductile behavior seen under off-axes loading is associated with significant void re-alignment with the load axis. Models in that direction exist [19]. The resulting increase in ductility is certainly of practical interest as pressure vessels are being increasingly fabricated through helical welding. (b) The evidence of multiple coalescence modes suggests that further analyses are required to understand better factors that limit ductility. The findings here suggest that the two-mechanism plasticity model [14] should be generalized to multiple mechanisms wherever appropriate. The occurrence of each mechanism should be microstructure as well as stress-state dependent. (c) Ductility of the studied steel is not nucleation-controlled. However, some qualitative insight was gained from observations. In particular, there seems to be a threshold for void nucleation in terms of a critical particle size. To our knoweldge, there is no model in the literature predicting such threshold. Whether the current characterization of the microstructure will be sufficient in modeling void nucleation, void rotation and selective coalescence modes remains an open question and requires further investigations.

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