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# Size effects in ductile failure of porous materials containing two populations of voids

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ABSTRACT

The ductile failure behavior of porous materials containing two populations of voids of different size is investigated numerically by means of 3D cell model calculations. In contrast to previous studies a non-local Gurson model is used to describe the secondary void population in the matrix material. Due to the internal length scale incorporated in the non-local model, it is possible to describe the size of the secondary voids in the matrix material. The results are obtained for loading states with different stress triaxialities and Lode parameters. The influence of the size of the secondary voids is analyzed and it is shown that larger secondary voids lead to a higher stress carrying capacity. This size effect is studied for different primary void arrangements. Furthermore, the strain and primary void volume fraction at the onset of coalescence are presented and cross references to experimental findings are drawn.


## 1. Introduction

Ductile fracture by void growth and subsequent coalescence is an important failure mechanism in metals. Therefore, many studies in the literature deal with this topic, for an overview see e.g. the review articles (Tvergaard, 1989; Benzerga and Leblond, 2010; Besson, 2010). Ductile failure consists of nucleation, growth and coalescence of microscopic voids. Void nucleation takes mostly place at inclusions or second-phase particles. Due to plastic deformation of the surrounding matrix material these voids start to grow. The onset of internal necking between the voids is caused by localization of plastic flow in the ligaments between the voids. This point corresponds to the start of acceleration of void growth leading to final failure by void coalescence.

In structural metals there are several types of defects with different sizes and mean spacings such as carbides, precipitates and non-metallic inclusions. Under mechanical loading voids nucleate first at the larger particles and start to grow. These large voids are referred to as primary voids within this paper. Upon further loading smaller secondary voids nucleate at the smaller particles so that there are now two populations of voids of different size scales. The final coalescence process between the larger voids can take place by two mechanisms (Faleskog and Shih, 1997; Benzerga and Leblond, 2010): Either there is coalescence by a flat rupture mode or by development of a micro shear band resulting in the so-called void-sheet formation. Which type of coalescence mechanism gets active depends on the applied type of loading and the microstructure of the material.

Fig. 1 shows two examples of fracture surfaces from materials with two populations of particles resp. voids on different length scales. In the low-alloyed German pressure vessel steel 22NiMoCr3-7 (see Fig. 1a) there are large primary voids originated at MnS inclusions and small secondary voids nucleated from $Fe_3C$ and $Mo_2C$ carbides (Seidenfuss et al., 2011; Seebich, 2007). Another material showing this phenomenon is nodular cast iron (see Fig. 1b), which consists of a ferritic matrix and nodular graphite particles with a void volume fraction of about 7–12%. Liu et al. (2002) found in experiments two mechanism of void coalescence in this material. For neighboring primary voids, which are originated from the graphite nodules, there is direct void coalescence by necking (top left in Fig. 1b) and on the other hand there is nucleation and growth of secondary voids nucleated from small particles (MnS, $Al_2O_3$, CaO) in the matrix material between wider spaced primary voids (center right in Fig. 1b). Notably, for both materials (steel and nodular cast iron) there are different relative reduction ratios of the remaining ligaments between differently spaced primary voids due to the limited ductility of the ligaments. Finally, ductile failure of these ligaments takes place due to coalescence of the microvoids.

An early description of ductile failure was realized by the analytical models of McClintock (1968) and Rice and Tracey (1969).

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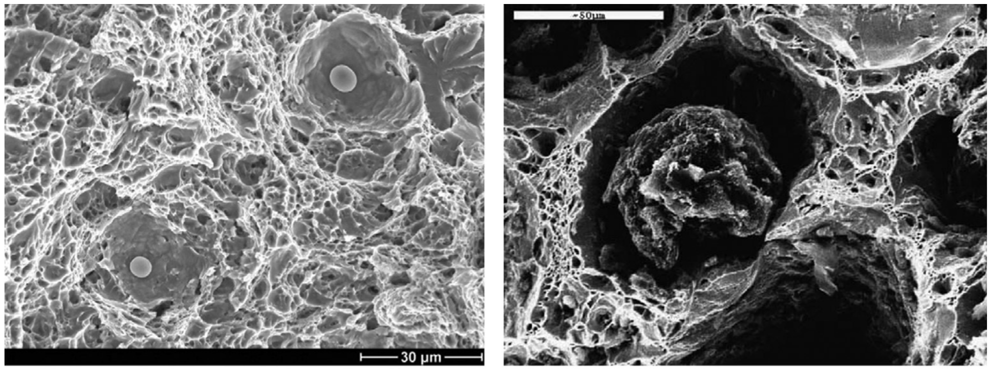


(a) (b)

**Fig. 1.** Ductile failure including secondary void population: Fracture surfaces including macro- and microvoids obtained (a) in 22NiMoCr3-7 (Seidenfuss et al., 2011) and (b) in nodular cast iron (Liu et al., 2002).

Constitutive equations for porous materials were established by Gurson (1977) and later by Rousselier (1987) based on homogenization theory, where a macroscopic yield criterion and an evolution law for the void volume fraction are included. Using micromechanical cell models, significant extensions have been made to the Gurson model by Chu and Needleman (1980), Tvergaard (1981), and Tvergaard and Needleman (1984), which are today known as the so-called GTN-model.

The finite element implementation of the GTN-model leads to a pathological mesh sensitivity of the results after the point of initiation of softening has been reached. Therefore, in order to overcome this drawback, so-called non-local damage models were developed in the last two decades. Regarding the GTN-model, either formulations of integral-type (Leblond et al., 1994; Tvergaard and Needleman, 1995; Jackiewicz and Kuna, 2003; Enakoutsa et al., 2007; Hu and Ghosh, 2008), of implicit gradient-enriched type (Reusch et al., 2003; Linse et al., 2012) or within the more generalized framework of higher order/strain gradient materials (Gologanu et al., 1997; Enakoutsa and Leblond, 2009) have been established. Common to all those formulations is that at least one internal material length is introduced. This regularization eliminates the mesh dependency of the numerical results. Furthermore, the internal length scale incorporated in non-local models can be somehow related to the microstructure of the material (Reusch et al., 2003).

Micromechanical finite element analyses with unit cells including discrete voids were used to investigate ductile failure of porous materials as well. Starting from the pioneering work of Needleman (1972), many studies with two-dimensional and axisymmetric unit cells (Tvergaard, 1982a,b; Koplik and Needleman, 1988; Brocks et al., 1995, among others) were performed in order to improve the phenomenological models mentioned above. Later, the influence of spherical voids was examined in three-dimensional calculations (McMeeking and Hom, 1990; Worswick and Pick, 1990; Richelsen and Tvergaard, 1994). The influence of different spatial void arrangements of the voids was investigated by Kuna and Sun (1996) for large porosities. Later, Zhang et al. (1999) also performed simulations for large void volume fractions with 3D unit cells containing voids of different size and arrangement. All the aforementioned studies show the influence of the stress triaxiality on the fracture strain, that is the higher the triaxiality the lower the fracture strain.

As pointed out by Benzerga and Leblond (2010), next to the stress triaxiality the dependence on the Lode parameter or Lode angle, as a measure of the effect of the third deviatoric stress invariant, should be taken into account within cell model simulations of ductile failure as well. Zhang et al. (2001) and Gao and Kim (2006) showed, that the Lode parameter has a large influence at low values of stress triaxiality. Furthermore, Barsoum and Faleskog (2007, 2011) and Nielsen et al. (2012) performed cell model analyses in order to study the influences of stress triaxiality and Lode parameter by allowing for a shear deformation of the unit cell in order to capture the mechanism of void coalescence by internal shearing.

Regarding the influence of an existing or nucleating secondary porosity, Faleskog and Shih (1997) performed micromechanical simulations under different strain biaxialities with discretely resolved secondary voids in order to study both mechanisms of ductile failure (flat rupture mode and void sheet formation). Furthermore, Brocks et al. (1995), Kuna and Sun (1996) and Gao and Kim (2006) performed unit cell analyses whereby a secondary population of voids was introduced by using the GTN-model for the matrix material. These investigations showed, that the effect of secondary voids is significant if the secondary voids are present right from the start and that it is negligible if the secondary population nucleates late. Note that the last studies are related to the flat rupture mode, where the failure is defined by the transition into a uni-axial straining mode. However, Tvergaard (1998) found in cell model analyses with discrete secondary voids, that a second population of microvoids does not affect the growth of the primary population. Furthermore, Fabregue and Pardoen (2008) showed that the second void population only influences the void coalescence.

Non-local models have also been used to model the secondary void population. Tvergaard and Needleman (1995) performed cell model calculations by using a non-local GTN-model. Thereby localization of plastic flow occurred in shear bands due to loading under uni-axial plane strain tension. The material length in the used non-local model was included by an integral formulation according to Leblond et al. (1994). However, the focus of this study was mainly on mesh dependence and performance of the non-local model without discussing the relation between internal length and microstructure. The intrinsic size effect for the coalescence of micron-sized voids was investigated by Niordson (2008) in cell model simulations using a non-local gradient hardening plasticity model. In this study the influence of the internal length on geometrical softening was investigated and no secondary porosity was assumed.

There are also constitutive equations for porous materials including two populations of voids, either derived by analytical