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# Size effects due to secondary voids during ductile crack propagation

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ABSTRACT

In the present study the size-effect due to a secondary void population during ductile fracture is investigated. Discrete primary voids are resolved in the process zone at the crack tip. A non-local GTN model is employed to describe the evolution of the secondary voids in the intervoid ligaments. The non-local GTN model contains an intrinsic length scale related to the size of the secondary voids. Hence, the ratio of the size of the primary and that of the secondary voids can be varied. The results show that small secondary voids can toughen the material. Such a behavior is in contrast to the prediction of cell model simulations. A theoretical reasoning of this effect and conclusions are given.



## 1. Introduction

Ductile failure is an important mechanism for the fracture of metals. The mechanism comprises the nucleation of microscopic voids at inclusions or second-phase particles, the growth of these voids and their coalescence. In many engineering metals different types of nuclei of void formation are present which differ typically in size, volume fraction and conditions of nucleation. They are mostly termed as populations of void nuclei. For instance, typical steels contain both, relatively weak inclusions such as manganese sulfide (MnS) inclusions and much smaller but harder carbide particles. The MnS inclusions are loosely bonded and nucleate voids early in the deformation process, whereas the debonding of the smaller carbides requires considerably higher plastic deformations. A corresponding fracture surface is shown in Fig. 1. Due to the relevance in engineering applications, the modeling of the ductile mechanism has attracted a lot of research efforts. In the following only a few key studies shall be discussed. Extensive reviews can be found in Tvergaard (1989), Benzerga and Leblond (2010) and Besson (2010).

The most widely used constitutive model to describe the void growth stage of the ductile mechanism was derived by Gurson (1977) by means of an analytical homogenization of a unit cell with ideal plastic matrix material. Here, the void volume fraction is introduced as intrinsic variable. Chu and Needleman (1980) presented an approach to incorporate the nucleation of voids. Tvergaard (1981, 1982) modified the model based on numerical simulations of a similar arrangement but with hardening matrix material (so-called cell model simulations). Furthermore, Tvergaard and Needleman (1984) extended the model to account for the stage of void coalescence. This model is today known as the Gurson–Tvergaard–Needleman model, abbreviated GTN.

In the nucleation approach by Chu and Needleman (1980), nucleated voids are added directly to the void volume fraction. Primary and secondary voids cannot be distinguished afterward. More sophisticated approaches were presented in Fabrègue and Pardoen (2008) and Perrin and Leblond (1990).

In many engineering metals one of the populations of voids nucleates early and at larger nuclei as described above. That is why this so called primary population is modeled in many studies (Tvergaard, 1982; Brocks et al., 1995; Fabrègue and Pardoen, 2008, among many others) as a priori existing and discrete void in a cell model whereas the secondary voids are incorporated in a smeared sense by employing the GTN model for the matrix material. The secondary voids affect mainly the initiation of the coalescence stage (Fabrègue and Pardoen, 2008).

In cell model simulations, the deformation state is assumed to be homogeneous with respect to the primary void. However, for practical applications the situation in front of a macroscopic crack tip is of great interest as well. Here, the deformations are highly non-homogeneous as sketched in Fig. 2. This problem was addressed by numerous researchers who resolved discretely a single void or several voids in front of the crack tip (see e.g. Aravas and McMeeking (1985), Gu (2000), Tvergaard and Hutchinson (2002), Gao et al. (2005), Petti and Dodds (2005), Tvergaard (2007), Chew et al. (2007), Hütter et al. (2012), Hütter et al. (2013) and Sreeramulu et al. (2013)). Aoki et al. (1984) and Aravas and McMeeking

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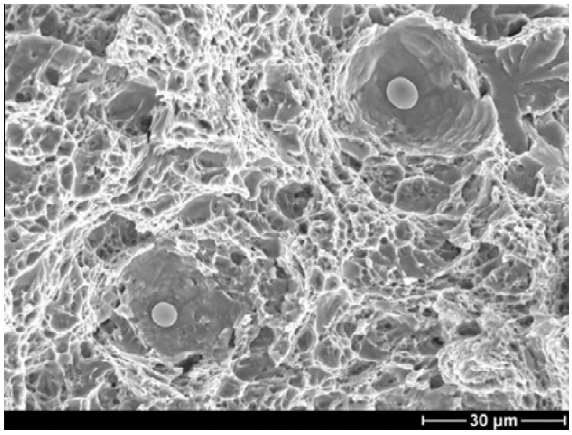


**Fig. 1.** Fracture surface after ductile failure in a pressure vessel steel (Seidenfuss et al., 2011).

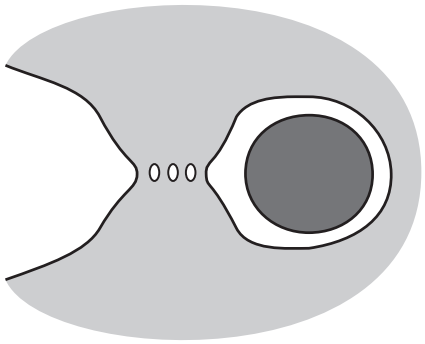

**Fig. 2.** Growth of secondary voids in front of a crack tip.

(1985) employed secondary voids in such a model by describing the matrix material by the GTN model as in the mentioned cell model simulations. In a similar approach the complete and compact domain is described by the GTN model but with islands of higher nucleable void volume fraction representing the primary voids (see e.g. Needleman and Tvergaard (1987) and Tvergaard and Needleman (2006)).

All of the aforementioned studies have in common that they incorporate the secondary voids only by their volume fraction within the theory of simple materials[1] and can thus not account for effects of the size of the secondary voids. This has the consequence that the respective boundary value problem has no physically meaningful solution if the growth of the secondary voids induces softening. This fact leads to the well-known problem of mesh-dependent results in corresponding finite element implementations.

This problem was addressed in Tvergaard and Needleman (1995) and Zybell et al. (in press) by using a non-local extension of the GTN-model for the secondary voids in the matrix material in cell model simulations. In non-local models an intrinsic length scale enters the constitutive description. This length is directly related to the spacing of the secondary voids. The results of the cell model simulations show that the smaller the secondary voids are compared to the primary ones, the earlier the primary voids coalesce.

Vernerey et al. (2008) presented a material model within the theory of micromorphic media that accounts for the size of the secondary voids, too. This model was used in Tian et al. (2010) together with discrete primary voids or islands of nucleable porosity at a crack tip to model crack propagation. These investigations focus on the simulation of the fracture initiation in a particular material, i.e. with stochastically aligned nuclei. The effect of the size of the secondary voids is not investigated. Size effects not due to secondary voids but due to gradient hardening of the matrix material were investigated in cell models (Niordson and Tvergaard, 2007) and with discrete voids at the crack tip (Tvergaard and Niordson, 2008). In both cases it is found that the void growth is retarded if the size of the voids is comparable to the characteristic length scale of the matrix material.

In the present study the size effect due to secondary voids during crack initiation and propagation is investigated in a two-dimensional model. For this purpose a number of discrete voids is resolved in front of a crack tip. The matrix material is described by the non-local GTN model by Linse et. al. (Linse et al., 2012; Hütter et al., 2013). This model belongs to the class of micromorphic media as well (Forest, 2009). A systematic parameter study is performed with respect to the size of the secondary voids and the nucleation parameters.

The paper is organized as follows. In Section 2 the employed model is presented. The global model of crack propagation is outlined in Section 2.1 before details of the non-local GTN model and of the numerical implementation are given in Sections 2.2 and 2.3. In Section 3 the model is preliminarily investigated in cell model computations before the actual fracture behavior is addressed in Section 4. The results are discussed in Section 5. Finally, Section 6 gives a summary and an outlook.

## 2. Model

### 2.1. Global model

The model to be investigated is sketched in Fig. 3. A number of regularly aligned and initially present primary voids of initial distance $X_1$ and volume fraction

$$f_{10} = \pi\left(\frac{R_1}{X_1}\right)^2 \tag{1}$$

are resolved discretely in the process zone. Here and in the following a subscript 1 refers to the primary void population and correspondingly 2 to the secondary one. Due to the computational effort, a plane model under plane strain conditions is considered thus corresponding to an infinitely thick specimen with cylindrical primary voids whose axes are aligned parallel to the crack front.

The matrix material between the voids is described by the non-local GTN model by Linse et al. (Hütter et al., 2013; Linse et al., 2012). Details of this model will be given in Section 2.2. This way the secondary voids are incorporated in a smeared way with the volume fraction $f_2$ and the intrinsic material length $l_2$. The smeared representation requires that the secondary voids are considerably smaller than the primary ones. The length $l_2$ is directly related to the distance of the secondary voids. Thus, the model is consistent only if $l_2$ is considerably smaller than $X_1$. However, no hard border between admissible and inadmissible values of the ratio $l_2/X_1$ can be given. For this reason most of the following simulations are performed in the regime $l_2/X_1 \leq 0.4$. Some results with a higher value of this ratio will be given which have merely a mathematical character as will be discussed at appropriate positions. The secondary voids can be initially present or can nucleate during the deformation process. Young's modulus and Poisson ratio of the matrix material are denoted as $E$ and $\nu$.

The material outside the process zone is described consistently by the GTN model (which is a special case of the non-local GTN

[1] The current state of a material point depends on the history of the deformation gradient at this point only.