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Non-uniform distributions of initial porosity in metallic materials affect the growth rate of necking instabilities in flat tensile samples subjected to dynamic loading

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ABSTRACT

In this paper we assess, using finite element calculations performed with ABAQUS/Explicit, the influence of porosity in the development of necking instabilities in flat metallic samples subjected to dynamic tension. The mechanical behaviour of the material is described with the Gurson–Tvergaard–Needleman [6, 22, 23] constitutive model pre-implemented in the finite element code. The novelty of our methodology is that we have included in the gauge of the specimen various non-uniform distributions of initial porosity which, in all cases, keep constant the average porosity in the whole sample. This has been carried out assigning random values of initial porosity (within specified bounds) to some nodes and zero to the others. Therefore, the larger the percentage of nodes with non-zero initial porosity, the smaller their initial value of porosity. The goal is to provide an idealized modelling of the distributions of void nucleating particles which in many structural metals nucleate early in the deformation process and lead to material porosity. The key point of this paper is that, following this methodology, we reproduce the experimentally-observed asymmetric-growth of the pair of necking bands which define the localization process in flat tensile samples subjected to dynamic loading [25].

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1. Introduction

The study of dynamic necking instabilities which trigger failure of metallic (ductile) samples subjected to impact tensile loading has focussed the efforts of many researchers over the last 80 years. The experimental works of Mann [12,13] in the 30s, and Clark and co-workers [3,4] in the 40s, were among the first papers in this topic. These authors performed tension tests using cylindrical specimens of different materials for impact velocities up to 100 m/s, and showed that the location of the neck in the sample, and thus the final fracture, was dependent on the applied velocity. This correlation between necking/fracture location and impact velocity was rationalized using the theory of plastic strain propagation that had just been developed by Von-Kármán [26]. It was concluded that the intervention of stress waves in the sample, generated due to the application of a sudden impact to a specimen at rest, yields severe strain gradients in the sample (spatial and temporal) which determine the position where the fracture occurs. Post-mortem examination of the specimens revealed considerable ductility inside the neck for all materials and velocities that these authors tested, the final fracture showing a deep cup and cone which were more *acute* as the impact velocity was increased. Similar experimental observations have been reported in many other studies in which metallic cylindrical bars were tested dynamically, see for instance the recent papers of Rittel and co-workers [17,18].

Since the 90s of previous century, using flat samples instead of round bars in the dynamic tensile testing of metallic materials has become a common practice. The main reason is the interest of the automotive industry in the mechanical characterization of metallic sheets used to build crashworthiness structures [2]. Using high speed servo-hydraulic machines, experiments in metallic sheets can be performed for velocities up to 20 m/s, and strain rates up to 10^3 s^{-1}. The failure of the sample is preceded by the formation of a pair of necking bands which are aligned with the two directions of zero extension contained in the plane of the specimen [7]. One of these bands grows faster than the other, leading to the formation of a single crack inclined 54.7° (if the material is isotropic) with respect to the loading direction.

Nevertheless, to the authors' knowledge, most of the attempts carried out so far to simulate numerically the tensile behaviour of flat samples subjected to dynamic loading predict that, contrary to the experimental observations, the growth rate of the pair of

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necking bands which form the localization process is largely similar [9,11,15,16,25]. It seems that, if the material is isotropic and homogeneous, and the boundary conditions ensure that the stress state in the sample is uniaxial until localization starts, there is not a perturbation in the numerical model that could lead to the asymmetric growth of the two bands. The mechanical perturbations coming from the propagation of waves within the specimen, and the numerical perturbations coming from the discretization of the work piece do not seem to produce an important difference in the rate of development of the necking bands. However, in some works, geometric perturbations have been included in the specimen model to trigger the asymmetric grow rate of the necking bands [14]. In this paper we propose a different approach, and develop a simple finite element model which, including non-uniform distributions of porosity in the specimen material, allows to reproduce the experimentally-observed asymmetric-growth of the pair of necking bands which define the localization process in flat tensile samples subjected to dynamic loading.

2. Constitutive framework

The mechanical behaviour of the material is described using the Gurson–Tvergaard–Needleman (GTN) constitutive model [6,22,23] pre-implemented in ABAQUS/Explicit [20]. For the sake of clarity, the main features of the model are briefly presented in this section.

The flow potential has the form:

$$\Phi = \left(\frac{\sigma_e}{\sigma_y}\right)^2 + 2q_1 f^* \cosh\left(\frac{3q_2\sigma_h}{2\sigma_y}\right) - 1 - (q_1 f^*)^2 \tag{1}$$

where the effective Mises stress, σ_e, and the hydrostatic pressure, σ_h, are defined by:

$$\sigma_e = \sqrt{\frac{3}{2}\boldsymbol{s} : \boldsymbol{s}}; \quad \sigma_h = \frac{1}{3}\boldsymbol{\sigma} : \mathbf{1}; \quad \boldsymbol{s} = \boldsymbol{\sigma} - \sigma_h : \mathbf{1} \tag{2}$$

where $\boldsymbol{\sigma}$ is the macroscopic Cauchy stress tensor, $\boldsymbol{s}$ is its deviatoric part, and $\mathbf{1}$ is the unit second order tensor.

Moreover, σ_y is the flow strength of the fully dense matrix material described in the present work by the following power-type relation [21]:

$$\sigma_y = \Psi\left(\bar{\varepsilon}^p, \dot{\bar{\varepsilon}}^p\right) = \sigma_0\left(1 + \frac{\bar{\varepsilon}^p}{\varepsilon_0}\right)^n \left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}\right)^m \tag{3}$$

where $\bar{\varepsilon}^p = \int_0^t \dot{\bar{\varepsilon}}^p(\tau)d\tau$ and $\dot{\bar{\varepsilon}}^p$ are the effective plastic strain and the effective plastic strain rate in the matrix material, respectively. Moreover, σ_0, n and m are material parameters, and ε_0 and $\dot{\varepsilon}_0$ are the reference strain and strain rate, respectively. Note that, for the sake of simplicity, the temperature dependence of the flow strength is not considered.

In Eq. (1), q_1 and q_2 are material parameters, and the function $f^* = f^*(f)$, where f is the void volume fraction, is given by:

$$f^* = \begin{cases} f & \text{if} \quad f < f_c \\ f_c + \dfrac{(f_u - f_c)(f - f_c)}{\left(f_f - f_c\right)} & \text{if} \quad f_c \leqslant f \leqslant f_f \\ f_u & \text{if} \quad f > f_u \end{cases} \tag{4}$$

where f_c is the void volume fraction at which voids coalesce, f_f is the void volume fraction at final fracture of the material and $f_u = 1/q_1$ is the ultimate void volume fraction.

The rate of deformation tensor is taken to be the sum of an elastic part, $\boldsymbol{d}^e$, and a plastic part, $\boldsymbol{d}^p$, as follows:

$$\boldsymbol{d} = \boldsymbol{d}^e + \boldsymbol{d}^p \tag{5}$$

Table 1
Material parameters used in the finite element calculations [21]. VVF stands for void volume fraction (porosity).

Symbol	Property and units	Value
ρ_0	Initial density (kg/m^3)	7600
G	Elastic shear modulus (GPa), Eq. (7)	26.9
K	Bulk modulus (GPa), Eq. (7)	58.3
q_1	Material parameter, Eq. (1)	1.25
q_2	Material parameter, Eq. (1)	1.0
σ_0	Reference yield stress (MPa), Eq. (3)	300
n	Strain hardening sensitivity, Eq. (3)	0.1
m	Strain rate sensitivity, Eq. (3)	0.01
ε_0	Reference strain, Eq. (3)	0.00429
$\dot{\varepsilon}_0$	Reference strain rate (s^{-1}), Eq. (3)	1000
f_0	Average value of initial VVF	0.01
f_c	VVF at which voids coalesce, Eq. (4)	0.12
f_f	VVF at final fracture, Eq. (4)	0.25
f_u	Ultimate VVF, Eq. (4)	0.8

where the elastic part is related to the rate of the stress by the following hypo-elastic law:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{C} : \boldsymbol{d}^e = \boldsymbol{C} : (\boldsymbol{d} - \boldsymbol{d}^p) \tag{6}$$

with $\dot{\boldsymbol{\sigma}}$ being the objective stress rate (it corresponds to the Green–Naghdi derivative in ABAQUS/Explicit [20]) and $\boldsymbol{C}$ being the tensor of isotropic elastic moduli given by:

$$\boldsymbol{C} = 2G\boldsymbol{I}' + K\mathbf{1} \otimes \mathbf{1} \tag{7}$$

where G is the elastic shear modulus, K is the bulk modulus and $\boldsymbol{I}'$ is the unit deviatoric fourth order tensor.

The plastic part of the rate of deformation tensor follows the direction normal to the flow potential:

$$\boldsymbol{d}^p = \dot{\lambda}\frac{\partial \Phi}{\partial \boldsymbol{\sigma}} \tag{8}$$

where $\dot{\lambda}$ is the non-negative plastic flow proportionality factor.

The plastic part of the rate of deformation tensor and the effective plastic strain rate in the matrix material are related by enforcing equality between the rates of macroscopic and matrix plastic work:

$$\boldsymbol{\sigma} : \boldsymbol{d}^p = (1 - f)\sigma_y \dot{\bar{\varepsilon}}^p \tag{9}$$

Moreover, assuming the incompressibility of the matrix material, the evolution of the void volume fraction is defined as:

$$\dot{f} = (1 - f)\mathbf{d}^p : \mathbf{1} \tag{10}$$

Note that void nucleation is not considered in the present analysis. Hence, if the initial void volume fraction is zero, the macroscopic material is fully dense and follows Mises plasticity.

In ABAQUS/Explicit, the integration of the constitutive model relies on the consistency condition during plastic loading:

$$\dot{\Phi} = 0 \tag{11}$$

Details regarding the integration of the constitutive model are not given herein but can be found in [1].

The flow strength of the matrix material, Eq. (3), has been used along with the GTN model pre-implemented in ABAQUS/Explicit through a user-defined subroutine VUHARD [20]. The material parameters related to the flow potential, Eq. (1), and the flow strength of the matrix material, Eq. (3), taken from [21], are given in Table 1. The average value of initial void volume fraction, from now on indistinctly referred to as porosity, is $f_0 = 0.01$ (average value over the whole gauge of the sample, see Section 3.2).

3. Finite element model

3D finite element simulations of flat tensile samples subjected to dynamic tension are carried out using the commercial finite element code ABAQUS/Explicit [20].

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