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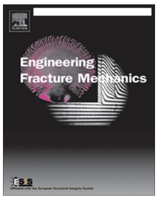

Characterization and modeling of the anisotropic damage of a high-explosive composition

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ABSTRACT

Modelling the behaviour of quasi-brittle materials requires dealing with the anisotropic damage evolution induced by the loading direction and the unilateral effect corresponding to the sudden opening/closure of defects. The latter was the cause deficiencies of some constitutive laws as a no continuous stress/strain response or spurious energy dissipation. In this paper, the behaviour of pressed high explosive is experimentally investigated. Evidences of a pre-existing damage, an anisotropic one developing during loading and the unilateral effect are detailed. The framework of the microplane constitutive laws previously proposed in the literature and based on the volumetric–deviatoric–tangential strain projections is used. Damage is introduced in the model and is affected by an "effectiveness" function weighting its influence with the loading direction. The calibration procedure is detailed and a discussion enables highlighting the strengths and weaknesses of the modelling approach.

1. Introduction

Modern numerical tools enable simulating operational life conditions of pyrotechnic structures as assembly/disassembly procedures or thermal cycles during storage. It requires an improved and accurate mechanical constitutive law of the explosive composition. A first difficulty comes from the complexity of the behaviour of such a material made of a high solid fraction of grains mixed with a polymeric binder. It gives a temperature and a strain rate dependencies as well as a dependence of the maximum stress with the confinement. A second difficulty comes from the experiments classically used to characterize such materials. Most of these are (1) monotonic ones with an increase of the load up to the failure and (2) strain measurement only made along the loading direction. These experimental set-ups hide some of the basic trends of the mechanical behaviour, and the calibration procedures of the models are questionable. Especially, the anisotropic nature of the damage cannot be observed, as well as the "unilateral" response of the material (for example the dependence of the Young's modulus with the loading direction) during tensile/compressive or compressive/tensile cyclic loadings.

The material studied in this paper is made of more than 95% by mass of octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) grains mixed with a low percentage of a binder. The mixture is pressed using an isostatic process. The final product can be machined into solid samples of various shapes. It behaves as a quasi-brittle material with a maximum strain of 0.01

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Nomenclature

a_i	calibration parameters
d_V, d_D, d_T	volumetric and out-of plane and in-plane shear damage variables, initial values
E, ν, K, μ	global Young's modulus, Poisson's ratio, bulk and shear moduli; experimental (resp. calibration) values with lowerscript "exp" (resp. "mod"), for compressive (resp. triaxial) tests with upperscript "H0" (resp. "H10")
E_L, E_T	longitudinal and transversal modules
F_V, F_D, F_T	volumetric, deviatoric and tangential forces associated to the damage variables
κ_V, μ_D, μ_T	volumetric and out-of plane and in-plane shear modulii
$\mathbf{n}$	microplane normal
q	state variable
$\mathbf{t}_\varepsilon$	strain vector
α_V, α_D	effectiveness parameters
ε_V, ε_D, $\boldsymbol{\varepsilon}_T$	volumetric, deviatoric and tangential strain
$\boldsymbol{\varepsilon}$	strain tensor
ψ, ψ^n	global and microplane free energies
ρ_0	density
$\boldsymbol{\sigma}$	stress tensor
σ_V, σ_D, $\boldsymbol{\sigma}_T$	volumetric, deviatoric and tangential stress

(respectively 0.001) recorded at the maximum stress during a compressive experiment (resp. a tensile one). During its operational life, this material is submitted to a hydrostatic pressure ranging between 0 and 10 MPa and few tensile/compressive loading cycles. The temperature and strain rate loading conditions being out of the scope of this paper, measurements will be reported below at ambient temperature and low strain rates (approx. 10^{-5} s^{-1}).

The microstructure of the material (Fig. 1 left) shows the distribution of the grain which sizes ranging from approximately 500 μm to less than a micron. It highlights the high density of pre-existing discontinuities (and thus defects) between grains. Porosity is mainly located between the smallest grains (dark zones in Fig. 1 come from optical aberrations due to small particles remaining at the surface of the polished sample). Due to the high pressure used to compact the aggregate, grains have been forced each to the other leading to intense stress at the contact zones. Intra-granular micro-cracks are observed as a consequence of this process. Randomly orientated grains, discontinuities and micro-cracks provide an isotropic response of the material confirmed by macroscopic measurements of the elastic modules whatever the direction the sample has been machined into a rough piece.

The sample has been submitted to a reverse edge-on compression test using the set-up described by Picart et al. [1]. This experiment enables observations at the surface of the sample during its deformation around a fixed wedge. Fig. 1 right shows (1) debonding between grains as the dominant mechanism of deformation at low confinement, (2) new intra-granular micro-cracks, (3) inelastic deformation of some grains along straight bands and (3) reorganization of the "matrix" (made by the smallest grains, the binder and the porosity). Damage is dominated by local tensile loadings, few shear strain being

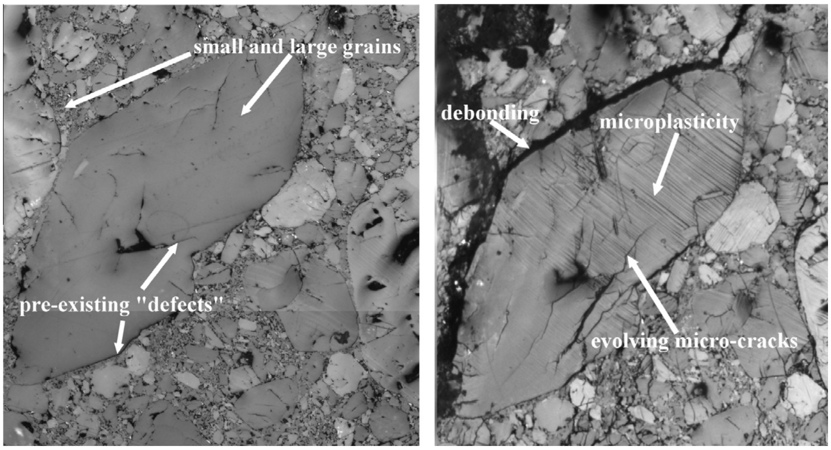

Fig. 1. Microstructural observations of a sample before (left) and after (right) a deformation at a low confinement. The first image highlights the dispersed sizes of the grains, pre-existing intra-granular micro-cracks due to the pressing process used to compact the powder and a lot of grain–grain surface contacts. The second one shows new micro-cracks due to debonding between grains, induced intra-granular micro-cracking and straight bands related to the inelastic deformation of some grains.

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