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Approaching steady cavitation: The time scale in hypervelocity cavity expansion in work hardening and transformation hardening solids

J.A. Rodríguez-Martínez [a, *], T. Cohen [b], R. Zaera [a]

[a] Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad, 30, 28911 Leganés, Madrid, Spain
[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

The extreme phenomena of dynamic cavitation is studied both theoretically and numerically for two families of strain hardening materials. Though analytical results are limited to the steady, self-similar expansion state, the numerical approach facilitates investigation of the transient response, including evaluation of the time required to approach the steady-state limit. While recent studies show that shock waves may appear in hypervelocity cavity expansion fields, the present study suggests a numerical model which can capture the appearance and evolution of these shock waves. That model is validated by comparison with theoretical results at the steady-state limit, thus facilitating future investigation of the dynamic response for materials with more complicated constitutive behavior, for which theoretical results are limited. The constitutive sensitivities are also examined, showing that the specific hardening response of the material has little effect on the cavitation response.

1. Introduction

Cavitation instability arises when an embedded cavity, within the solid, expands spontaneously upon application of constant load, subjected either at the cavity wall or in the remote field. That critical level of load, to induce cavitation, is the quasistatic cavitation pressure. If the applied load is higher than that critical level then dynamic cavitation will evolve implying that the cavity expands with finite velocity. If the applied load is lower than that critical level then the solid will find a new configuration of static equilibrium.

Over the years, cavitation phenomena has been widely accepted as a basic mode of failure in solids. Following the early study by Bishop et al. [1], which suggested that the resisting pressure in the indentation process is the spherical quasistatic cavitation pressure, extensive research has been devoted to the relation between cavitation phenomena and other material instabilities, including penetration and perforation phenomena and fracture initiation. Cavitation has been experimentally observed in a variety of materials ranging from ductile metals [2], to biological soft tissue [3]. Though most available research on cavitation phenomena focuses on quasistatic fields (see an extensive review by Horgan and Polignone [4] for hyperelastic solids and by Cohen et al. [5] for elastoplastic solids), it is understood that high velocity penetration processes are related to dynamic cavitation [6].

Available theoretical studies on dynamic spherical cavity expansion [7–12] focus on hardening and non-hardening elastoplastic solids and pressure sensitive materials. In those studies the theoretical formulation of the field response bypasses the transient behavior by assuming a self-similar expansion. While most studies on dynamic cavity expansion are limited to moderate velocities, it was recently shown, in Refs. [11,12], that at hypervelocities plastic shock waves may appear. Therein the dynamic response is fully accounted for by exposure of a singularity in the governing field equations and application of Hugoniot jump conditions. Ortiz and Molinari [13] studied the strain rate effects in dynamic spherical cavity expansion for incompressible hardening elastoplastic solids, thus accounting for the transient response but without the appearance of shock waves.

It is conceivable that the appearance of shock waves in the material response can have a dramatic effect on the resistance of the solid to penetration, and it is therefore essential to obtain an in depth understanding on the evolution of these shock waves. Hence, the present study attempts at a computational model of dynamic cavitation which agrees with the theoretical models at the steady-state limit and is able to predict the transient behavior, including the time required for appearance of the theoretical steady-state response. Once that model is verified it can be extended to

* Corresponding author. Tel.: +34 916248460; fax: +34 916249430.
E-mail address: jarmarti@ing.uc3m.es (J.A. Rodríguez-Martínez).

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account for more complicated material response for which theoretical predictions do not exist, including strain rate effects and thermo-mechanical coupling.

In the present study a computational model is developed and compared with results obtained according to the theoretical framework for dynamic spherical cavity expansion proposed in Refs. [8,10,11]. First, a work hardening material response is considered, similar to that in Cohen et al. [11], then the model is extended for a family of *strain induced martensitic transformation* (SIMT) materials for which theoretical modeling is limited. While the first hardening mechanism accounts for strengthening of the material by dislocations accumulation, the second one is equivalent to a dynamic composite effect due to the progressive transformation of austenite (softer phase) to martensite (harder phase) upon deformation. This is a characteristic of multiphase TRIP steels and metastable austenitic grades, that are widely used for energy absorption in crash or blast protection applications [14–18]. It has to be noted that the behavior of solids showing martensitic transformation at high strain rates has been recently analyzed in perforation [19] and dynamic necking [20,21] problems. These works identified loading conditions and characteristics of transformation kinetics for which martensitic transformation delays plastic localization and boosts the energy absorption capacity of the material. However, little is known about the role played by martensitic transformation in development of cavitation instabilities.

The hardening response of metal alloys plays an important role in their application to protective structures due to increased energy absorbing capabilities. On that note, appearance of plastic shock waves is also necessarily involved with dissipation due to entropy rise manifested by a jump in temperature across the shock [22,23]. Hence, better understanding of the role of shock waves in the dynamic material response, and the related constitutive sensitivities, can lead to development of more efficient protective materials in the future.

Rosenberg and Dekel [24] presented a 2D numerical investigation of the dynamic cavitation response of perfectly plastic materials in the context of long-rod penetration mechanics. In the present work we extend that numerical framework to more complicated material response and at hypervelocities to observe the appearance of plastic shock waves. An essential feature of the present study is in understanding the transient response, or namely, the time required to approach the steady field. Since steady cavitation fields are being applied in prediction of penetration and perforation [24,25], it is important to understand the relevant time scales. If the penetration process is much faster than the time required for steady cavity expansion to appear then steady cavitation fields are not sufficient in underlying the physical phenomena.

As described in Section 2, the constitutive model is based on the standard principle of Huber–Mises plasticity accounting for finite strains and two different strain hardening mechanisms: work hardening and martensitic transformation hardening. Work hardening materials are defined by a simple Ludwik hardening law, whereas transformation hardening materials are described as in Zaera et al. [21]. In Section 3 we shortly recapitulate the analytical investigation of the steady cavitation fields for arbitrary hardening response, with earlier reference to Durban and Fleck [8] and Masri and Durban [10]. The appearance of shock wave discontinuity and application of jump conditions at the shock is accounted for as in Cohen et al. [11] and Cohen and Durban [12]. The numerical model is presented in Section 4, followed by analysis and results in Sections 5 and 6. Section 5 focuses on the evolution of the steady field and shock wave propagation, and Section 6 examines the constitutive sensitivities. Section 7 outlines the main outcomes of this study.

2. Constitutive model

As stated before, to obtain a better understanding of the constitutive sensitivity of dynamic cavitation, we consider two different strain hardening mechanisms: work hardening and martensitic transformation hardening. The main hypothesis of the constitutive models used in the present analysis centers on the standard principles of Huber–Mises plasticity: hypoelastic behavior, additive decomposition of the rate of deformation tensor, isotropic hardening, associated flow rule and plastic power equivalence

$$\boldsymbol{\sigma}^{\nabla} = \mathbf{C} : \mathbf{d}^e = \mathbf{C} : (\mathbf{d} - \mathbf{d}^p) \tag{1}$$

$$\Psi = \overline{\sigma} - \sigma_Y = 0 \tag{2}$$

$$\mathbf{d}^p = \frac{\partial \Psi}{\partial \boldsymbol{\sigma}} \dot{\overline{\varepsilon}}^p = \frac{3\mathbf{s}}{2\overline{\sigma}} \dot{\overline{\varepsilon}}^p \tag{3}$$

where $\boldsymbol{\sigma}^{\nabla}$ is an objective derivative of the Cauchy stress tensor, $\mathbf{d}$, $\mathbf{d}^e$ and $\mathbf{d}^p$ are the total, elastic, and plastic rate of deformation tensors respectively, $\mathbf{C}$ is the Hooke tensor for isotropic elasticity (defined by Young modulus E and Poisson ratio ν), Ψ the yield function, $\overline{\sigma}$ the equivalent stress, $\dot{\overline{\varepsilon}}^p$ the equivalent plastic strain rate, σ_Y is the yield stress and $\mathbf{s}$ the deviatoric stress tensor. The reference values that will be considered for E, ν, as well as for initial mass density, are given in Table 1.

Next, we present the models used to describe the two aforementioned hardening processes. It is worth noting that both processes have been intentionally uncoupled in our study in order to uncover separately the influence of each one in the process of cavity expansion. Thus, plastic strain has been considered as the unique source of work hardening, whereas phase transformation has been considered as the unique source of transformation hardening. Certainly both effects are ultimately triggered by plastic deformation, but the functional dependence of the yield stress on strain greatly differs among them.

2.1. Work hardening material

For the work hardening material, the value of the yield stress is given as a function of the equivalent plastic strain $\overline{\varepsilon}^p$ through a widely used power law (frequently referred to as the Ludwik hardening law)

$$\sigma_Y = A + B(\overline{\varepsilon}^p)^k \tag{4}$$

The reference values of the material parameters A, B and k are given in Table 2.

2.2. Transformation hardening material

Based on the earlier study by Olson and Cohen [26] and assuming that intersection of shear bands in the austenite is the dominant mechanism of SIMT, we suggest a model which captures the martensitic transformation by considering the closed-form

Table 1
Reference elastic properties and density for work hardening and transformation hardening materials.

Symbol	Property and units	Value
E	Young modulus (GPa)	200
ν	Poisson ratio	0.33
ρ_o	Initial density (kg/m^3)	7800