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ScienceDirect

Procedia Engineering 197 (2017) 252 – 259

Procedia Engineering

www.elsevier.com/locate/procedia

DYMAT 23rd Technical Meeting

Dynamic Fracture of Ductile Materials

A damaged medium model for describing dynamic spallation fracture

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Abstract

The main physical laws of the failure process in structural materials under dynamic loading modes and mathematical models of such processes are considered. To describe dynamic spallation fracture, a version of governing equations of damaged medium mechanics is developed, consisting of three interrelated parts: governing equations describing plastic behavior of the material as a function of the failure process, evolution equations of damage accumulation, and a strength criterion of the damaged material. A methodology for determining material parameters of kinetic equations of damage accumulation, based on minimizing the quadratic deviation between theoretical and experimental data is used. Comparison of the obtained computational results with the experimental data on dynamic spallation fracture in plates during plane impact shows that the present model of damaged medium mechanics adequately describes experimental data and can be effectively used in analyzing dynamic spallation fracture.

Peer-review under responsibility of the scientific committee of the International Conference on Dynamic Fracture of Ductile Materials

Keywords: dynamic deformation; stress waves; spallation; modeling; damaged medium mechanics; stressed-strained state; material parameters; damage degree; failure.

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Peer-review under responsibility of the scientific committee of the International Conference on Dynamic Fracture of Ductile Materials
doi:10.1016/j.proeng.2017.08.102

1. Introduction

Experiments with such materials as aluminum, copper, beryllium, steel, Armco-iron, quartz, and polycarbonate, which are very different in their structure and properties, showed [1–5] that the process of dynamic spallation fracture has a universal character. When the striker impacts the target, compression waves propagate on both sides of the contact boundary, their amplitude being determined by the impact velocity. Having reflected from the free surface as relaxation waves of the opposite direction, they create in the target an area subject to the effect of tensile stresses. When the stresses reach their threshold value, the damage accumulation process starts. With the increase of their concentration, unloading of the material takes place in the zone of growing cavities, resulting in the propagation of a spallation pulse on both sides of the failure zone. Active stresses lead to the nucleation of a large number of defects (microcracks and micropores), which grow as long as the stresses remain above a certain threshold value. The nucleated defects merge into a main crack or form several main cracks, or else a dense crack net develops in the body, resulting in spallation fracture. The described failure process in solids under dynamic loading differs from the quasi-static one (in particular, from the fatigue one), where damage localization takes place at earlier stages, and the bodies normally fail completely as a result of propagation of a single main crack. As crack propagation velocities in the majority of cases are much lower than stress wave propagation velocities, the resulting microcracks do not have enough time to propagate very far. This explains why a tested specimen, when spalling, can sustain tensile stresses two orders of magnitude as high as its static strength.

In works [1–5], a failure process in the course of pulsed loading is assumed to be of the two main types: viscous or brittle. The viscous type is characterized by the growth of nearly-spherical micropores, whereas the brittle one is characterized by the formation of penny-like microcracks.

The appearance of numerous defects can lead to changes in the mechanical properties of the material, which, in its turn, affects the kinetics of stresses, strains and the failure process. Currently, to evaluate dynamic strength of solids, damage accumulation theories are commonly used. These works make use of models of damaged medium mechanics (DMM), which are based on the concept of a measure of damage, a quantitative characteristic of the degree of damage of materials.

The most comprehensive and developed model of dynamic spallation fracture, accounting for the nucleation and growth of microdefects, is the NAG (nucleation and growth) model introduced in [1–3]. The NAG model was developed based on experimental investigations with a quantitative analysis of microdefects. The model discerns two types of spallation with damage. The model requires a large number of experimentally determined parameters for kinetic relations of nucleation and growth of discontinuities, which involves considerable experimental difficulties when determining them. This is especially the case when modeling the microdefect nucleation phase, at which defects do not affect physical-mechanical properties of materials. At this stage, parameters can be determined only with the help of the methods of physics of metals, which significantly complicates practical application of the NAG model.

Another phenomenological approach uses a scalar measure of damage, which, as a rule, is introduced axiomatically, taking no account of the size and form of microdefects [6, 7, 9]. In this sense, damage is analogous to the volumetric content of microcavities. The simplest case in such an approach consists in assigning a measure of damage using scalar function $\omega(t)$, which can assume values from ω_0, corresponding to the undamaged state, to ultimate value ω_f, corresponding to failure. At the same time, damage is defined with an evolution equation of the form determined based on theoretical reasons and a limited number of basic tests.

To correlate processes of deformation and damage accumulation, various model representations are used in governing equations of damaged media. In [1–3, 12] the effect of defectiveness on the mechanical properties is accounted for, using an equation of state of continuum. A damaged condensed medium with microcavities is viewed in [8, 11] as a mixture of two phases: the first phase is the undamaged part of the medium, the second one is microcavities. An averaged stress tensor of the damaged medium is represented by a function of concentration of microdefects and stresses of the continuous medium.

Physical-mechanical properties of damaged media are a complex and little-studied function of its state. In practice, simplified relations are normally used: to characterize the stressed state, the notions of effective stresses or effective elasticity moduli [6] are introduced.