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SCATTERING AS A MECHANISM FOR STRUCTURED SHOCK WAVES IN METALS

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ABSTRACT

The scattering of wave energy during shock propagation through heterogenous media is examined as an alternative to visco-plasticity as the physics underlying the formation of structured steady shock waves in polycrystalline metals. A theory based on a quasi-harmonic representation of scattered acoustic energy in solids is pursued and used to develop continuum constitutive relations to describe nonlinear wave propagation in heterogeneous solids. Resulting constitutive models are compared with shock wave profile data for metals. © 1998 Elsevier Science Ltd. All rights reserved.

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INTRODUCTION

Barker (1968) reported on experimental measurements of structured shock waves in aluminum providing one of the first demonstrations of the excellent temporal resolution of the velocity interferometry diagnostic methods in shock wave physics. Early theoretical work (e.g., Band and Duvall, 1961) referred to an underlying solid viscosity as the property responsible for the observed finite rise-time in steady structured shock waves. The early Russian literature also attributed effects observed in the shock wave environment to viscous characteristics of solids (e.g. Mineev and Savinov, 1967). From the aluminum data of Barker (1968) it was noted that this viscosity lessened with the shock amplitude giving rise to a very strong increase in the steepness of the shock wave with shock amplitude. In fact if a strain rate $\dot{\varepsilon}$ was identified at the fastest rising portion of the structured steady wave it was found that the strain rate increased with the shock amplitude p according to $\dot{\varepsilon} \sim p^4$ while the viscosity η was observed to lessen as $\eta \sim \dot{\varepsilon}^{-1/2}$ (Grady, 1981). Structured steady-wave data on a range of metals were subsequently reported by Swegle and Grady (1985) and showed the same fundamental trends with variation in shock amplitude suggesting a universal behavior in the nature of structured steady waves in metals.

These structured shock-wave data for metals have led to a number of efforts to develop descriptive constitutive models (e.g., Johnson, 1992, Swegle and Grady, 1985; Rubin, 1990; Partom, 1990). Such models were generally based on formalisms of

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visco-plasticity and have been reasonably successful in describing the trends in the experimental data. These previous modeling efforts tacitly assumed, of course, that the underlying physics of time-dependent plasticity processes (dislocations, twinning, etc.) are responsible for the dissipation and wave dispersion leading to observed structured shocks in metals. Visco-plasticity may, in fact, be the responsible physics but there are other viable physical mechanism which could account for the observed results that have not been adequately discounted.

An alterative mechanism, for example, which could account for the observed structured shock waves in metals is suggested by ultrasonic experiments of Mason and McSkimin (1947) on aluminum. Their work shows that the attenuation of ultrasonic waves above a frequency of about several megahertz is dominated by scattering within the grain structure of the polycrystalline metal. Acoustic scattering would lead to wave dispersion at any amplitude and could also counterbalance the shock-up tendency of nonlinear solids accounting for observed structured shock waves.

There can be little doubt that scattering plays a role in the propagation of large amplitude shock waves in metals. Whether scattering is principally responsible for the observed shock wave structure is the critical question.

With these brief remarks serving to introduce the nature of the topic of interest the remaining portion of the introduction will outline the objectives and briefly summarize the results of the present paper. It is suggested first that wave scattering may be responsible for the finite width structuring of shock waves in polycrystalline solids. Earlier ultrasonic data on wave scattering in metals are then summarized and serve to motivate ideas of wave scattering when material is subjected to large amplitude shock waves. Such ideas have received only the briefest of attention in earlier shock wave literature. Consequently, a substantial portion of the paper focuses on identifying the physics and developing a model descriptive of the processes by which shock waves scatter acoustic energy and which accounts for the subsequent representation of that energy. It is found that a quasi-harmonic theory of matter previously used to develop equilibrium thermal properties of solids can be extended to the problem of acoustic scattering, providing both a vehicle for clarifying the physics and a framework for modeling the phenomena.

This physics-based model is found to lead to continuum constitutive relations which are formally the same as governing relations arrived at by Barker (1971) and by Kanel' *et al.* (1995) on a more intuitive basis. It is shown that such relations based on the physics of acoustic wave scattering quite adequately model the structured steady shock-wave data for metals.

The results therefore leave open the question of whether visco-plasticity or wave scattering provides the dominate underlying physics responsible for observed behavior of structured steady waves in metals. Single-shock steady-wave data are not sufficient to discern between the constitutive models resulting from the two physical theories.

This observation opens the question of whether more complex large amplitude wave profile data would provide the test for distinguishing between the theories. It is noted that some two-step steady shock data exists for selected metals, providing an interesting alternative loading path for testing the models. Such data for aluminum are examined and it is found that the continuum models based on the physics of wave scattering which satisfactorily predicted the single-step steady shock data are unable