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TITLE: SHEAR WAVE MEASUREMENTS IN SHOCK-INDUCED, HIGH-PRESSURE PHASES

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SHEAR WAVE MEASUREMENTS IN SHOCK-INDUCED, HIGH-PRESSURE PHASES.*

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Structural phase transformations under shock loading are of considerable interest for understanding the response of solids under nonhydrostatic stresses and at high strain-rates. Examining shock-induced transformations from continuum level measurements is fundamentally constrained by the inability to directly identify microscopic processes, and also by the limited number of material properties that can be directly measured. The latter limitation can be reduced by measuring both shear and compression waves using Lagrangian gauges in combined, compression and shear loading. The shear wave serves as an important, real-time probe of the shocked state and unloading response. Using results from a recent study of $CaCO_3$, the unique information obtained from the shear wave speed and the detailed structure of the shear wave are shown to be useful for distinguishing the effects of phase transformations from yielding, as well as in characterizing the high-pressure phases and the yielding process under shock loading.

INTRODUCTION

Understanding how nonhydrostatic stresses and high strain-rates can produce observed increases in structural phase transformation kinetics under shock loading is of fundamental, as well as practical, interest. Continuum level investigations of shock-induced transformations suffer from the inability to identify microscopic processes directly. Nonetheless, the full potential of continuum measurements has not been achieved because only longitudinal stress and particle velocity can be measured reliably, which leaves the deviatoric and mean stresses undetermined.

Measuring both shear and compression waves using embedded particle velocity gauges in combined, compression and shear loading plate impact experiments augments continuum measurements with new information that is directly related to both the shear properties and mean stress of the shocked material.[1,2] The shear wave is a useful probe of the shear properties of the compressed state produced by the faster traveling compression wave. It is not of practical use for mapping the yield surface by varying the shear and compression wave amplitudes in successive experiments: The shear stress carried in the compression wave is ~50% greater than that in the shear wave (assuming a manageably large inclination of $\theta \sim 20°$ and Poisson ratio of 0.25). For a von Mises yield, this corresponds to the longitudinal stress at yield being only 12% less than for uniaxial strain alone ($\theta=0°$).

The efficacy of measuring both shear and compression waves for studying phase-transforming materials has been demonstrated recently in an investigation of polycrystalline $CaCO_3$, where it has been valuable for distinguishing effects of phase transformations from yielding and for characterizing both the high-pressure phases and the yielding process.[3,4] Analogous results have been obtained or should be obtainable in non-phase-transforming materials. In contrast to previous results,[1,2] in the phase-transforming material mean stress could not be directly computed from the experimentally-determined bulk modulus values.[4]

EXPERIMENTAL METHOD

In-material, electromagnetic gauges at selected depths measure transverse and longitudinal particle velocity histories associated with the propagation of large amplitude, one-dimensional compression and shear waves. These waves are generated by parallel impact of two plates that are equally inclined to their direction of approach. The magnetic field and gauge orientations are chosen so that, under ideal conditions, the gauges respond to either longitudinal or transverse motion.[5]

Two experiments are needed at each impact velocity due mainly to the impracticality of placing more than four gauges in a sample.[6] In the first, we simultaneously measure the longitudinal and transverse motions with two gauges set at the same depth from the impact face. This measurement is important for correlating the shear and compression wave arrivals precisely when the latter has a complex structure due to yielding or structural phase transformations.[5] In the duplicate experiment, we measure the longitudinal histories, only, at three depths to permit calculation of longitudinal stress and strain fields.

RESULTS

These measurements provide the following information at each impact velocity: Shock wave speed; shear and longitudinal wave speeds at the peak compression; longitudinal stress longitudinal strain paths; shear stress shear strain paths. The shear and bulk moduli are obtained from the wave speeds and density. Measurements at a series of impact velocities provide the density variation of the moduli in the shocked state.

A series of compression shear experiments on Carrara marble samples at peak levels from 0.5 GPa to 6.3 GPa longitudinal stress demonstrate the possibility and value of measuring both shear and longitudinal waves in phase transforming materials.[3,4] Mechanical yielding and two phase transformations occurred within this range. These processes prevented neither shear wave propagation nor the particle velocity measurements. Details of the response of $CaCO_3$ are reported in [3] and [4]. Here we focus on two comparisons afforded by the shear wave measurements that help greatly in distinguishing phase transformations from yielding and in characterizing the high pressure phases and yielding process.

In Figure 1 the bulk modulus values in the shocked marble are plotted versus peak density compression. The open squares are estimates based on the measured release wave speed.[4] Because the elastic moduli as functions of density (not stress) represent the same physical quantities under shock and hydrostatic loading, the bulk modulus values permit a more discriminating comparison of material response under these loading conditions than do wave speeds. The solid line represents the isentropic bulk modulus values determined from ultrasonic wave speed measurements on Oak Hall limestone.[7] The two sets of broken lines give the isothermal bulk modulus values determined from hydrostatic compression curves for single crystal calcite in [8] (dashed) and [9] (short dash). Values from a finite strain fit to the latter hydrostat are shown by the bold dashed line.[4] The stability fields of the three phases observed under room temperature hydrostatic compression are indicated by the horizontal arrows.

The bulk modulus in the shocked marble shows the expected decrease due to changes in elastic properties across the transformation to $CaCO_3$(II) and a subsequent increase that is comparable to that observed under hydrostatic loading up to the start of the $CaCO_3$(III) stability field. At 11% compression, the shocked marble bulk modulus lies far below the value determined from the hydrostat.[4]

Because the bulk modulus is rather insensitive to deformation or yielding, this discrepancy suggests the onset of a transformation to a phase other than $CaCO_3$(III) that has a substantially lower bulk modulus. The bulk modulus of compressed aragonite is not known, but it is the likely candidate for this new phase. This is supported by the calcite Hugoniot crossing the $CaCO_3$(III) segment of the hydrostat by 14% compression and merging with the aragonite Hugoniot.[4]

In previous compression shear studies[1,2] the mean stress in the shocked state was calculated from the density integral of the bulk modulus.

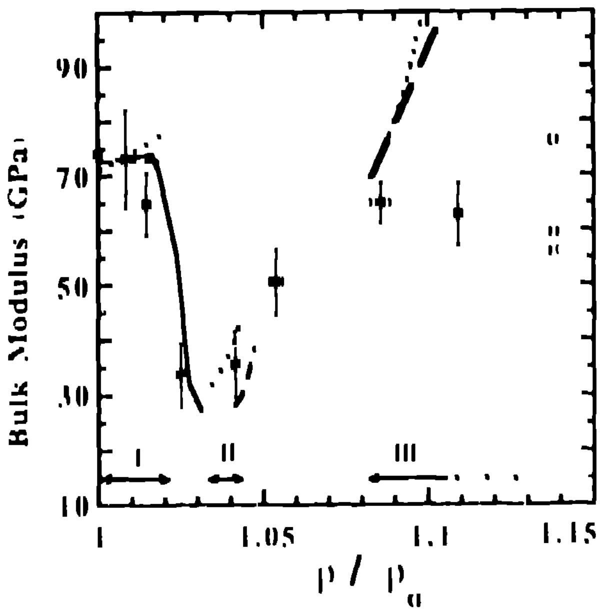

Figure 1. Bulk modulus in shocked Carrara marble (squares) versus normalized density compared with hydrostatic data (see text)

Mean stress values are needed for separating deviatoric stress and strain-rate effects on materials response. Without them the usefulness of continuum shock wave measurements is curtailed substantially. Integrating the bulk modulus values shown in Figure 1 leads to unphysical negative stress deviators in the mixed-phase region. In phase-transforming materials the mean stress cannot be directly computed in this manner apparently because the experimentally-determined bulk modulus values in the mixed-phase region are frozen phase-composition values and so are not equal to the logarithmic density derivative of the Hugoniot mean stress.

The difficulty in calculating the Hugoniot mean stress can be understood by considering the schematics shown in Figure 2. In Figure 2a, the dashed curve is an idealized compression curve for a single crystal that undergoes a first-order phase transformation. The Hugoniot mean stress for a polycrystal of this same material is represented by the solid curve. Figure 2b shows the corresponding bulk modulus-density relations. The single crystal modulus is taken to decrease across the transformation, as is observed for calcite. The solid curve gives the relaxed polycrystal bulk modulus, K_{rlx}. The relaxed and frozen modulus, K_{frz}, values at 3% compression are indicated by the dot and open circle, respectively; frozen modulus values are always intermediate between the pure component values.

The Hugoniot mean stress can be obtained by integrating the bulk modulus provided the latter corresponds to the slope of the mean stress-density curve. In the mixed phase region K_{rlx} is systematically lower than K_{frz} because it includes the contribution from the volume change of the transformed fraction of the sample. The speed of the, ideally, infinitesimal amplitude leading edge of the release wave is used to determine the bulk modulus. As no change in phase composition occurs in the leading edge, the measured wave speeds are frozen phase composition values. Consequently, integrating the experimentally determined bulk modulus density relation overestimates the mean stress and can lead to apparent strain softening or even negative stress deviators.

The shear wave amplitudes can provide information about material strength that cannot be obtained from the wave speeds or the compression wave amplitudes. In phase transforming materials

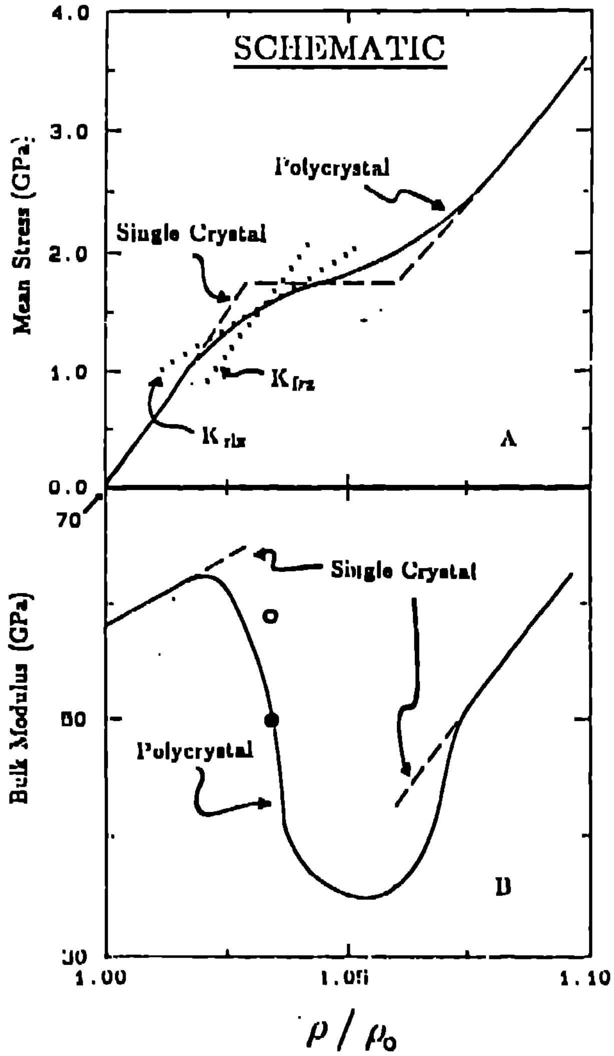

Figure 2. Schematic of responses governed by frozen and relaxed bulk moduli.

this additional information can be important for distinguishing the effects of yielding from phase transformations. However, numerical simulations of the wave propagation using assumed material models are needed to analyze shear wave amplitudes.[10] Nonetheless, it is readily apparent that, because shear wave amplitudes are related to material strength, the ability of the marble to support finite amplitude shear waves indicates that it retains significant strength up to 6.3 GPa.[4]

Gupta's simulations illustrate the approach for analyzing shear wave amplitudes. He demonstrates that the shear wave is sensitive to the yield process during longitudinal unloading.[10,11] Hence, combined with numerical simulations, the shear wave history during longitudinal unloading can be used to detect yielding and characterize portions of the yield surface.

Qualitative aspects of the marble strength response were inferred by comparing the results of Gupta's simulations for granite with the shear wave particle velocity histories in Carrara marble:[11] The marble yields due to passage of the compression wave, alone, at a longitudinal stress of 1.55 GPa or less; the marble exhibits yield behavior that resembles a pressure-dependent response.

CONCLUSIONS

The investigation of Carrara marble demonstrates that shear waves can be measured in a material undergoing shock-induced phase transformations and that these measurements provide additional information not obtainable from uniaxial strain, plate impact experiments. The shear and longitudinal wave speeds, together with calculated peak densities,[12] provide shear and bulk moduli values of the high-pressure phases. In mixed-phase regions the moduli so determined are frozen phase-composition quantities.

The Hugoniot mean stress cannot be directly computed from these bulk modulus values. There is currently no proven method for determining the Hugoniot mean stress in an arbitrary solid. Lateral stress gauge measurements might eventually provide this crucial capability (in this regard see M. K. W. Wong in these Proceedings). Nonetheless, the bulk modulus data provide strong additional constraints on material models.

Shear wave amplitudes can be useful for characterizing inelastic response, but they do not permit simple determination of the yield surface.

Together the shear and compression wave measurements more fully characterized the shocked state, but they were insufficient for answering many specific questions about the dynamic response of calcite rocks, even on the continuum level.[4] It was beneficial to the investigation that the first phase transformation was rapid, easily identifiable, and occurred within a stress range that was easy to study.

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