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SHOCK COMPRESSION AND RELEASE OF POLYCRYSTALLINE MAGNESIUM OXIDE

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Release wave profile and Hugoniot equation of state data for low-porosity polycrystalline MgO are reported to 36 and 133 GPa, respectively. At low pressure, the Hugoniot lies above single-crystal data, reflecting material strength of 3.1 ± 0.8 GPa. Unloading wave velocities to 27 GPa are consistent with extrapolated compressional sound velocities. The unloading profiles can be fit using a viscoplastic model, but there are significant differences between waveforms for different experimental geometries.

INTRODUCTION

Magnesium oxide is of geophysical interest because it is potentially a major constituent of the Earth's lower mantle. Its exceptional stability from ambient conditions to pressures above 200 GPa under both dynamic and static loading also makes it a significant material for study. Previously, wave profile data on single-crystal MgO shocked between 4.8 and 11.2 GPa were reported [1]. Study of polycrystalline MgO is of interest because of the wide range of response of ceramic materials to shock deformation [2]. In this work, we have measured the equation of state (EOS), unloading wave velocities, and wave profiles on nearly fully dense polycrystalline MgO under shock compression.

EXPERIMENTAL METHOD

Samples

Low-porosity polycrystalline magnesium oxide (MgO) samples were obtained commercially (Cercom Inc.) as 1.25" diameter hot-pressed disks. Microprobe analysis revealed the presence of less than 0.5% impurities. The average crystal density was found via the Archimedeian method to be 3.571 ± 0.004 g/cm³, and the average bulk density obtained by weighing and measuring the samples was 3.562 ± 0.006 g/cm³, both of which are within better than 1% of the x-ray density (3.584 g/cm³). Sample flatness variations were less than 0.01 mm. The

longitudinal sound velocity was measured ultrasonically to be 9.81 km/s.

Equation of State Experiments

Equation of state experiments were conducted on MgO specimens using both a propellant and a light gas gun. The velocity of Ta and Mg flyer plates was measured to ~ 0.1 -1% by recording x-ray shadowgraphs immediately prior to impact. Wave velocities were determined from the destruction of flat and inclined mirrors in contact with the sample and the driver plate. The measured shock and flyer plate velocities were combined with impedance-matching techniques and the Rankine-Hugoniot equations to constrain the shock velocity, particle velocity, stress, and density of the shock-compressed state.

Wave Profile Measurements

Wave profile measurements were conducted for both forward and reverse ballistics geometries using a VISAR. In the reverse impacts, a 3-4 mm thick MgO sample was used to impact a 2-mm thick Al 6061 buffer with an LiF window (8-mm thick) attached to it. The sample was backed by low-density foam. In the forward geometry, an MgO flyer was used to impact an MgO target to which a 2-mm thick Al 6061 buffer and an LiF window (8-mm thick) were attached. The combined thickness of the MgO flyer and sample was nominally 7 mm in these experiments. In both geometries, the VISAR was

used to monitor the velocity of the buffer-window interface. A total of five reverse ballistic and four forward ballistic experiments were performed.

RESULTS

The Hugoniot states determined from the EOS experiments are shown in Fig. 1 and Table 1. Also shown in Fig. 1 are single-crystal Hugoniot data [3] for MgO. The elastic precursor was resolved in only one experiment from which a velocity of 9.77 ± 0.12 km/s was obtained, in agreement with the ultrasonically measured value.

Wave profiles representing a subset of the reverse and forward ballistic experiments are shown in Figs. 2 and 3. Some chaotic variations in particle velocity are evident in the velocity plateau region. This may reflect differential motion of grains, material reorganization, or heterogeneous faulting and has been observed previously in ceramics [2]. The measured interface particle velocities are consistent with values calculated using the equation of state discussed below.

Unloading wave velocities were determined from the reverse-impact experiments (Fig. 4) using the arrival time difference between the shock and unloading waves. Shock states in the buffer and sample were determined from the particle velocity at the buffer-sample interface and impedance matching. Unloading wave velocities in the buffer were determined from the time difference between the shock and the arrival of the reverberation through the buffer.

DISCUSSION

Equation of State

While single-crystal and porous polycrystalline MgO have been studied extensively using shock techniques, the present study represents the first EOS determination for low-porosity (<1%) polycrystalline MgO. The shock velocity-particle velocity data of Table 1 can be described by the relation:

$$U_S = 6.87 (0.10) + 1.24 (0.04) u_p \quad (1)$$

where U_S is the shock velocity and u_p is the particle velocity. For MgO, the bulk velocity from ultrasonic data [4] is 6.73 km/s, which is 2.1% below the U_S - u_p intercept. Also shown in Fig. 1 is the static isotherm

Figure 1. Stress-density states achieved in shock compression of MgO. Open symbols are for single-crystal MgO. Solid symbols are data of this study. The solid curve is a fit to the present Hugoniot data and the dashed curve is the static isotherm [4].

for MgO constructed from 0-3 GPa ultrasonic elasticity data [4] and the Birch-Murnaghan equation. The polycrystalline MgO data lie above the single-crystal data at low stresses and above the static isotherm at all stresses. The coincidence of the single-crystal data and the static isotherm at low stresses has been used to infer that MgO undergoes a significant loss of strength above the Hugoniot elastic limit [1]. In contrast, magnesia does not undergo such a collapse. Below 56 GPa, the stress difference between the static isotherm and the polycrystalline Hugoniot data is 1.5-2.5 GPa, when thermal effects have been subtracted by employing the Mie-Grüneisen equation. For an elastic-plastic material, the yield strength is three-halves the stress difference between the Hugoniot and the static isotherm, implying that the yield strength of polycrystalline MgO is 3.1 ± 0.8 GPa at these stresses.

Table 1. EOS experiments on polycrystalline MgO.

Experiment	u_p (km/s)	U_S (km/s)	σ (GPa)	ρ (g/cm ³)
233	3.37(1)	11.04(7)	132.6(8)	5.13(3)
840	0.89(1)	7.96(11)	25.3(3)	4.00(2)
841	1.74(2)	9.01(13)	55.9(9)	4.42(3)
843	0.51(1)	7.53(12)	13.8(2)	3.83(2)

Unloading Wave Velocities

Compressional and bulk sound velocities were calculated to 30 GPa from ultrasonic data [4] extrapolated using finite strain theory [5]. The results are shown in Fig. 4 along with measured Hugoniot unloading velocities plotted as a function of mean pressure. The Hugoniot unloading velocities agree with the ultrasonic extrapolations within their experimental precision (2-3%). This implies that the unloading wave is traveling with the compressional elastic wave velocity and that extrapolation of ultrasonic data is suitable over this pressure range.

Using the finite strain equations, Hugoniot measurements can be inverted to obtain elastic moduli and their pressure derivatives along the Hugoniot. By combining the present Hugoniot data with the ambient-pressure compressional velocity, the following values for the longitudinal elastic modulus, C_{LO} , and its pressure derivative C'_{LO} are obtained: $C_{LO} = 335 \pm 1$ GPa and $C'_{LO} = 7.0 \pm 0.4$. The ultrasonically determined parameters are: $C_{LO} = 336.9 \pm 0.3$ GPa and

Figure 2. Interface particle velocity histories for reverse impacts. Peak stresses are listed next to each profile. The times are arbitrary and have been shifted for display purposes. Points are experimental data, curves are wavecode simulations.

$C'_{LO} = 7.4 \pm 0.2$ [4]. Thermal effects on the compressional sound velocity are calculated to be less than 1% at these pressures.

Grady [1] reported three wave profiles on single-crystal MgO shocked along [100] between 4.8 and 11.2 GPa (mean pressures of 3.5 - 9.9 GPa). The initial unloading velocities are 4-6% below the ex-

trapolated sound velocity in this direction at high pressure (Fig. 4). Single-crystal MgO collapses to the hydrostat upon shock compression above the HEL. The unloading wave velocities indicate that material strength has recovered substantially in the ~500 ns time interval between shock and release arrivals. The different behaviors of polycrystalline and single-crystal MgO are a reflection of different yielding processes in single and polycrystals.

Constitutive Modeling

Numerical simulations of the particle velocity histories were carried out using WONDY [6]. Models tested included an elastic perfectly plastic (EPP) model as well as those including a Bauschinger effect and strain-rate dependent stress relaxation. The Al

Figure 3. Interface particle velocity histories for forward impacts.

6061 buffers were described using the viscoplastic model of [7]. The LiF windows were treated as elastic perfectly plastic.

The EPP model could not fit the wave profiles in detail but revealed that the measured profiles were not significantly dispersive. The amplitude and shape of the precursor transmitted through the buffer in the forward impacts could only be matched by MgO yield strengths between 1-1.5 GPa, while the initial unloading of the reverse impacts was best fit by a yield strength of 2.5 GPa. The precursor velocities in the forward experiments were variable and could not be reproduced consistently.

Separate viscoplastic models which included a Bauschinger effect and stress relaxation were arrived

at for the forward and reverse experiments (Figs. 2 and 3). While the main features of the profiles can be fit with a simple model, there are some complicating features. The reverse impacts exhibit significantly sharper initial releases than the forward impacts. This may be an indication of non-steady wave propagation. A large fraction of the sample in the forward impacts is subjected to partial unloading due to wave reflection at the sample-buffer interface. This may produce a damaged region that could affect subsequent unloading waves. The lowest-amplitude reverse experiment has a weak and diffuse elastic release, similar to the forward impacts. This illustrates that the shape of the profile in MgO is dependent both on peak stress and propagation distance.

SUMMARY

Equation of state and wave profile measurements have been performed on low-porosity (<1%) polycrystalline MgO. The equation of state differs from single-crystal MgO, reflecting different levels of strength in single and polycrystals.

Wavecode simulations of the particle velocity histories were performed to assess whether a viscoplastic material model could accurately describe the dynamic behavior of MgO. While reasonable fits were obtained, separate models were required for the forward- and reverse-impacts because of the different nature of the waveforms observed

Figure 4. Unloading wave velocities in MgO. The solid symbols are for polycrystalline MgO, and the open symbols are for single-crystals shocked along [100][1]. The solid curves are extrapolated ultrasonic data, and the dashed curve shows the expected effect of Hugoniot temperature on V_p . The dotted curve shows the extrapolated compressional velocity along [100].

under these two conditions.

There are several lines of evidence which suggest that polycrystalline MgO, in contrast to single crystals, retains its strength when shock-compressed in the 10-37 GPa range. First, the temperature-corrected stress-volume states measured in the EOS experiments lie 1.5-2.5 GPa above the hydrostat. Second, the initial unloading wave velocity corresponds to extrapolations of ultrasonically measured compressional wave speeds. Third, the initial portion of the unloading wave, particularly for the reverse experiments, is sharp and non-dispersive.

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REFERENCES

- [1] D. E. Grady, "Processes occurring in shock wave compression of rocks and minerals", in *High-Pressure Research: Applications to Geophysics*, 1977, pp. 389-438.
- [2] M. E. Kipp and D. E. Grady, "Shock compression and release in high-strength ceramics", *Sandia Natl. Lab., Rep. SAND89-1461*, 1989.
- [3] W. J. Carter, S. P. Marsh, J. N. Fritz, and R. G. McQueen, "The equation of state of selected materials for high-pressure reference", in *Accurate Characterization of the High Pressure Environment*, 1971, pp. 147-158.
- [4] I. Jackson and H. Niesler, "The elasticity of periclase to 3 GPa and some geophysical implications", in *High Pressure Research in Geophysics*, 1982, pp. 93-133.
- [5] C. Sammis, D. Anderson, and T. Jordan, *J. Geophys. Res.*, 75, 4478-4480 (1970).
- [6] M. E. Kipp and R. J. Lawrence, "WONDY V - A one-dimensional finite-difference wave propagation code", *Sandia Natl. Lab., Rep. SAND81-0930*, 1982.
- [7] R. J. Lawrence and J. R. Asay, "High-pressure multiple-shock response of aluminum", in *High Pressure Science and Technology*, 1979, pp. 88-98.