Anisotropic Hugoniot elastic limit of MgO

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Abstract. The particle velocity profiles of an MgO single crystal were measured along both <100> and <110> directions using a LiF window and a VISAR (velocity interferometer system for any reflector) combined with a powder gun. The Hugoniot elastic limit (HEL) of MgO in the <100> direction was ~4.09–4.31 GPa and the particle velocity profiles indicated that MgO suffers stress relaxation with time. Along the <110> direction, the HEL was higher (~13.6-14.9 GPa) than along the <100> direction and Anomalous, two-step-structure elastic waves were observed. These characteristics are discussed based on the slip system of the MgO crystal.

1. Introduction
The normal stress at which yielding happens during uniaxial shock loading is called the Hugoniot elastic limit (HEL). It has long been pointed out that the anisotropic HEL values of single crystal can help us to understand its yield mechanism during shock loading [1-3]. In this study, we focus on the orientation-dependent elastic–plastic transition of single-crystal MgO. MgO was chosen because of its wide industrial application and geophysical importance [4,5].

Along the <100> direction, Ahrens reported that the HEL of MgO increases with increasing final pressure (3.5 and 8.9 GPa at final pressures of 16.6 and 42.3 GPa, respectively) and decreases with shock propagation distance [6]. Grady’s VISAR (velocity interferometer system for any reflector) results also show that the HEL of MgO increases with driving force (2.1, 2.3 and 2.6 GPa at final pressures of 4.8, 8.2 and 11.2 GPa, respectively) [7]. However, recent VISAR results of Stevens et al. shown that the HEL of MgO is higher than 2.7 GPa, and when the final pressure is higher than 16.6 GPa, the HEL shows a slightly decrease with increasing final pressure [8]. In the present study, we measured the particle velocity profiles of MgO single crystals along both the <100> and <110> directions using a VISAR combined with a LiF window. This work helps to clarify the contradictory results in the literature and also to understand the yielding mechanism of MgO.

2. Experimental methods
The single-crystal MgO samples were supplied by Dalian Keri Optoelectronic Technology Co. Ltd., China. They were grown by the arc melting method and had a purity better than 99.95%. Samples were 12 mm × 15 mm rectangles with a thickness of ~2–3 mm, both sides of the samples were
polished with 800-grit sandpaper. LiF single crystals with diameter of ~9 mm and thickness of ~4 mm, oriented at <100> were used as the windows. The windows were first polished to an optical finish on both sides, and then 500-nm gold films were vacuum vapor deposited on the backing surfaces. The MgO sample and LiF window were held together by a ~1–2-μm-thick epoxy layer. Experimental configuration is shown in figure 1. Plate impact experiments were performed on a 27-mm bore-keyed powder gun with a maximum flyer velocity of 2 km/s [9]. The flyer and driver plate were copper or tungsten with a thickness of ~1 or 1.5 mm. Two electrical pins separated by a distance of ~14 mm were mounted on the driver plate to monitor the inclination of the flyer and also to trigger the recording system. The flyer inclination angles on our powder gun have been measured to be small (less than 1°) by several 10s of shots using the high-speed streak camera system and pin contactor method in our past study. So, we only monitored the inclination along one direction in this study. The flyer velocities were measured by the electromagnetic method [10]. A VALYN VISAR apparatus of model VLNV-04-DD-C0 [11,12] was used to measure the interfacial particle velocity between MgO sample and LiF window.

The typical interference fringe pattern and the deduced interfacial particle velocity are shown in figures 2 and 3, respectively. The interfacial particle velocity first increases to a peak value, which is the HEL of MgO, and then decreases a little because of stress relaxation. After that, on the coming of the plastic wave, it increases again and keeps at nearly constant until the coming of the rarefaction wave. We performed two shots along both <100> and <110> directions, the results are shown in figures 4 and 5, respectively.

**Figure 1.** Experimental configuration.

**Figure 2.** Interference fringe pattern of shot MgO-<100>-1.

**Figure 3.** Interfacial particle velocity of shot MgO-<110>-1.
3. Results and discussions
Along <100> direction (figure 4), with final pressure increase, the HEL shows a slight decrease. The HEL determined by impedance match method between MgO sample and LiF window are 4.31 and 4.09 GPa with final pressure at 16.3 and 22.0 GPa, respectively. The HELs are higher than Grady’s results, but in consistent with those of Stevens et al. It is possible that the very large HEL value of 8.9 GPa reported by Ahrens is not accurate. The HEL decreasing a little with increasing driving force, this phenomenon has also been found on CaF, which may have been caused by stress relaxation [13]. We noticed that for the higher pressure one, the particle velocity profile contains 2 peaks, and in both cases, there is a kink before HEL. This characteristic was also observed in reference [8], in which a symmetry impact configuration (the flyer, sample and window were all single-crystal MgO) was used, we thus can exclude the effect of impedance mismatch. To our understanding, this phenomenon may be caused by inhomogeneous deformation. Grady pointed out that differential motion on a scale less than the VISAR spot size will lead to a reduction in VISAR contrast because the interference maxima and minima at different points within the spot will occur at different times [14]. Along the <110> direction, the HEL increases with final pressure as shown in figure 5. Abnormal three-wave structures were observed in both experiments, which may have been caused by an inversion of the slip system, shock-induced cracks or inhomogeneous deformation. A similar three-wave structure has also been observed by Mashimo et al. in LiF for a shock along both the <100> and <110> directions [15]. The intensities of the first waves are 5.53 and 8.25 GPa, and those of the second waves are 13.6 and 14.9 GPa, with final pressures at 24.9 and 35.0 GPa, respectively. The Hugoniot pressures in the experiments were calculated based on the time interval between the elastic and plastic waves according to the analysis described in ref.[10]. The elastic wave velocities used in the calculation were 9.39 and 10.28 km/s along the <100> and <110> directions, respectively. These values were taken from our unpublished flat-mirror data. Along <110> direction, to our calculation, the second wave travels at a velocity around 9.5 km/s, close to the longitudinal sound velocity of MgO, which indicates that it is an elastic wave. This double yield phenomenon may be explained by the inversion of the slip systems.

At ambient conditions, the main slip system of MgO is {110}<110>, and the {100}<110> slip system can become active at high pressure or high temperature [16,17]. When compressing along the <100> and <110> axes, according to the on dimension strain analysis, the resolved shear stresses (RSS) on the {110}<110> slip system are 0.339σx and 0.144σx, respectively, in terms of the applied stress σx. A smaller RSS on the main slip system explains the higher HEL along the <110> direction. Shock recovery experiments have found that when shock along the <100> direction, the majority of slip takes on {110} planes. And when shock along <110> direction, though {110} slip predominates, {100} and {211} slip are relatively plentiful [18]. The inversion of the slip planes from {110} to {100} at high pressure has been predicted by Amodeo et al. between 30 and 60 GPa based on first principles

Figure 4. Interfacial velocity profiles along <110> direction.

Figure 5. Interfacial velocity profiles along <110> direction.
calculations [19] and by Girard et al. at 23 GPa and 1000 °C based on X-ray synchrotron radiation analysis [20]. We conclude that when shock along the <110> direction, the {110}<110> slip system becomes active first, and then the {100}<110> slip system becomes more active under the high pressure and temperature produced by the shock wave. The inversion of slip system induced the observed three-wave structures. Along <100>, the HEL shows a slight decrease with shock pressure, while along <110> direction, it increases with shock pressure, this phenomenon may also be explained by the slip system. We conclude that for a shock compressing along the <100> direction, slip can easily occur on the main slip system and the shear bands produced by slip induce the stress relaxation. On the other hand, when the shock is along the <110> direction, several slip systems were activated. The interaction of the slip systems forms irregular twins and dislocations, which induce the toughening.

4. Conclusion
In summary, we studied the anisotropic deformation of MgO under shock loading by measuring the particle velocity profiles between the MgO and LiF window along both the <100> and <110> axes. The HEL shows an obvious orientation dependence that can be explained by the slip systems. Abnormal three-wave structures were observed when the shock was along the <110> axis, which may have arisen from inversion of the slip systems, cracks or inhomogeneous deformation. The mechanism that governs this process requires further investigation.

References
[1] Murri W J and Anderson G D, 1970 J. Appl. Phys. 41 3521
[2] Graham R A and Brooks W P, 1971 J. Phys. Chem. Solids 32 2311
[3] Mashimo T, Nagayama K and Sawaoka A, 1983 J. Appl. Phys. 54 5043
[4] Murakami M, Ohishi Y, Hirao N and Hirose K, 2009 Earth Planet. Sci. Lett. 277 123
[5] Duffy T S and Ahrens T J, 1995 J. Geophys. Res. 100 529
[6] Ahrens T J, 1966 J. Appl. Phys. 37 2532
[7] Grady D E 1977 High pressure research: Applications in Geophysics, (New York: Academic Press) p 389
[8] Stevens G D, Veeser L R, Rigg P A and Hixson R S, 2006 AIP Conf. Proc. 845 1353
[9] Mashimo T, Ozaki S and Nagayama K, 1984 Rev. Sci. Instrum. 55 226
[10] Mashimo T, Zhang Y, Uchino M and Nakamura A, 2009 Jpn. J. Appl. Phys. 48 096506
[11] Barker L M and Hollenbach R E, 1970 J. Appl. Phys. 41 4208
[12] Barker L M and Hollenbach R E, 1972 J. Appl. Phys. 40 4669
[13] Sekine T and Kobayashi T, 2011 Phys. Chem. Minerals 38 305
[14] Grady D E, 1994 Journal De Physique IV 4 C8-385
[15] Mashimo T, Nakamura M and Uchino M, 1997 AIP Conf. Proc. 429 439
[16] Hulse C O, Copley S M and Pask J A, 1963 J. Am. Ceram. Soc 46 317
[17] Patel A R and Sutaria J N, 1971 J. Phys. D: Appl. Phys. 4 1586
[18] Klein M J and Edington J W, 1965 Phil. Mag. 14 21
[19] Amodeo J, Carrez P and Cordier P, 2012 Phil. Mag. 92 1523
[20] Girard J, Chen J and Raterron P, 2012 J. Appl. Phys. 111 112607