J. Phys. Chem. Solids, 1971, Vol. 32, pp. 2311–2330. Pergamon Press. Printed in Great Britain.

SHOCK-WAVE COMPRESSION OF SAPPHIRE FROM 15 TO 420 KBAR. THE EFFECTS OF LARGE ANISOTROPIC COMPRESSIONS*

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(*Received* 14 *January* 1971)

Abstract—Under shock compression, sapphire (crystalline Al_2O_3) exhibits Hugoniot elastic limit, HEL, values of from 120–210 kbar; the largest values observed for any solid. Because of the large HEL, the stress configuration of the shock-loaded sample is highly anisotropic. A critical examination of the effects of large anisotropic stresses on the compression of solids is accomplished with shock experiments on sapphire in three crystallographic directions at stress values within the elastic range to stress values up to twice the HEL. The maximum shear strengths observed range from 4·9 to 5·6 per cent of the shear modulus. When stresses in excess of the HEL are achieved, sapphire is observed to undergo a catastropic loss of shear strength; in contrast to the yield behavior observed for metals. The results are compared to observations on high density polycrystalline Al_2O_3 and other solids with large HEL values. The behavior of sapphire is found to be analogous to that previously observed for crystalline SiO_2. Data in the elastic range show a third order elastic constant $C_{111} \approx C_{333} = -(3{\cdot}6 \pm 0{\cdot}4) \times 10^{13}$ dyne/cm². Analytical methods are developed to determine the shear stress offset independent of the hydrostatic data.

1. INTRODUCTION

COMPRESSION measurements for hydrostatic pressures greater than a few tens of kbars are difficult to accomplish and limited in accuracy [1]. Ultrasonic measurements of compressibility and its pressure derivative can be precisely determined but are limited to modest pressures [2]. Consequently, shock-wave compression measurements, which may be accomplished at very high pressures, are frequently employed to provide data which may be used to calculate high pressure isothermal compression curves [3] or to test extrapolation of ultrasonic data to very high pressure [2]. Unfortunately, data from shock compression experiments are not directly comparable to either ultrasonic data or static high pressure isothermal data. The experimental conditions of the shock experiment not only include heating due to the rapid compression but also include a potentially large shear stress component which is an inherent property depending upon the shear strength of the solid. Early shock compression workers usually assumed that the shear strength of solids was negligible so that the shock compression was isotropic and the calculation of an isothermal compression curve from the shock data was concerned only with thermodynamics of the shock heating and the equation-of-state of the solid [4]. It is now widely recognized that the effect of shear strength of the solid must be evaluated before hydrostatic and shock compression data can be directly compared. Unfortunately, the shear strengths of solids under shock-wave compression have not received as much study as thermodynamic effects and are not well enough understood to evaluate their effects unequivocally.

The object of the present paper is to evaluate shear strength effects in solids which exhibit unusually large shear strengths with correspondingly large anisotropic compressions. After introducing basic concepts of the stress configurations imposed by shock-loading and

*Work supported by the U.S. Atomic Energy Commission.

the shear strength, the existing models for the effects of shear strength of solids on the compressions experienced in a shock compression experiment will be reviewed. Following this, an experimental study of the shock compression of sapphire (single crystal Al_2O_3) will be described and the results will be presented and examined for shear strength effects. A determination of several higher-order elastic constants will also be presented. The results of the present investigation will then be used along with the other data in the literature to assess the present understanding of shear strength effects in solids under shock compression.

2. BACKGROUND

(a) *Shear strength of solids*

Shock loading a sample with the detonation of a high explosive[5], the impact of a projectile[6, 7], or the rapid deposition of radiant energy[8] produces an inertial response with pressures and pressure-time histories which depend upon the compressional properties of the sample. When the sample is loaded over a large planar area the compression is uniaxial, i.e., a state of uniaxial strain is achieved for times less than that required for unloading pulses to arrive in the test area. If the sample has a finite, i.e., non-zero, shear strength, the stress configuration is not isotropic since the resulting inertial stress components normal to the shock compression direction are less than the stress component in the shock propagation, or axial, direction. The shock experiment measures only the stress component in the axial direction while the lateral stress components can only be inferred by indirect means. Moreover, the axial component of stress will be larger than the isotropic pressure at the same compression to an extent depending upon the magnitude of the shear component of stress. The relation between the isotropic and anisotropic compressions must be known before the shock data can be converted to equivalent isotropic compression conditions.

The magnitude of the shear may be expressed in terms of the stress component, σ_x, measured in the shock experiment and a mean pressure value by considering an anisotropic stress configuration and defining a mean pressure, $\bar{P}$, as

$$\bar{P} \equiv \tfrac{1}{3}(\sigma_x+\sigma_y+\sigma_z). \quad (1)$$

If a solid is laterally isotropic the lateral stress components are equal, i.e., $\sigma_y = \sigma_z$. Equation (1) may then be rearranged such that

$$\bar{P} = \sigma_x - \tfrac{2}{3}(\sigma_x-\sigma_z). \quad (2)$$

The maximum value of the shear stress, τ_{max}, is

$$\tau_{max} = \tfrac{1}{2}(\sigma_x-\sigma_z), \quad (3)$$

thus,

$$\bar{P} = \sigma_x - \tfrac{4}{3}\tau_{max}. \quad (4)$$

It will be convenient in what follows to refer to the difference between σ_x and $\bar{P}$ as the *shear stress offset* defined as

$$\sigma_\tau \equiv \sigma_x - \bar{P}. \quad (5)$$

The determination of differences between longitudinal shock compression stresses, σ_x, and hydrostatic pressures, P, at the same volume could provide an experimental measure of the shear stress offset. However, as previously indicated, measurements of both σ_x and P are normally not available in the same high pressure range and it is desirable to evaluate σ_τ independently so that measurements of σ_x may be used to compute $\bar{P}$.

Since the strain configuration is known to be uniaxial and since solids are frequently observed to behave elastically up to a yield stress value in shock compression called the Hugoniot elastic limit, HEL, the shear stress value at the HEL can be computed assuming that Hooke's law is valid. In this case

$$\tau^* = \tfrac{1}{2}[(1-2\nu)/(1-\nu)]\sigma_H \quad (6)$$