has been critically examined by Grover [70G2, 71G4, 73G7]. These static data were obtained by use of a piston-cylinder apparatus and are limited to pressures below 4.5 GPa. This limit is below the range of most shock-compression measurements so that comparison is to an extrapolated shock isotherm. The comparisons are in terms of tabular values of the ratio of compressed to original sample volume (v/v_0) and disagreements amount to only a few tenths of 1 per cent in most cases. This comparison is somewhat deceiving, however, because the total compressions are very small. A more easily interpreted comparison would be of the compressions, $1 - (v/v_0)$, in which case the difference between the shock and static values is typically 5 per cent.

The use of isotherms extracted from Hugoniot data for standardization of marker materials seems reasonable subject to the reservations expressed previously about obtaining equation-of-state information from Hugoniot data. The uncertainties are reduced when ductile metals are used in pressure ranges where the thermal pressure is small. Carter et al. [71C2] and Fritz et al. [71F2] have discussed the suitability of a number of materials for this purpose and Mao et al. [78M2] have continued this work, with specific attention to the use of copper, molybdenum, palladium, and silver in the pressure range from 6 to 100 GPa. Some further attention to the behavior of these materials and interpretation of available data would seem indicated, but there is reason to believe that they do permit establishing pressure to an accuracy of a few per cent. The internal consistency of the results for the four metals is most encouraging.

The linear (U, u) Hugoniot relation of eq. (2.16) is equivalent to a Hugoniot relationship between pressure and specific volume. Making certain reasonable assumptions, Ruoff [67R4] has shown that the coefficients of eq. (2.17) are given by

$$a = (K^s/\rho^+)^{1/2}, \qquad b = \tfrac{1}{4}[1 + \mathrm{d}K^s/\mathrm{d}p] \tag{3.6}$$

where K^s and $\mathrm{d}K^s/\mathrm{d}p$ are the isentropic bulk modulus and its pressure derivative, respectively, at the initial state. The value of a given by eq. $(3.6)_1$, can be identified with the isentropic bulk sound speed.

Ruoff and Chhabildas [77R3] have compared piston-cylinder, ultrasonic, and shock determinations of the isothermal bulk moduli and their first pressure derivatives for the alkali halides. Comparison of these parameters is a very sensitive test of agreement, which is found to be reasonable in most cases. The comparisons do show that, almost without exception, the shock-compression experiment yields a larger value for the modulus and a smaller value for its derivative than the ultrasonic measurement. Comparison with piston-cylinder data shows more variation but a similar trend is apparent. This trend has been noted previously by Pastine and Piacesi [66P1] and it seems reasonable to interpret it as evidence for nonlinearity in the (U, u) Hugoniot curve as they have done.

Syassen and Holzapfel [78S6] have recently found that X-ray data to 12 GPa for aluminum disagree with shock and ultrasonic data by less than 1 per cent for the bulk modulus and 3 per cent for its derivative. The corresponding values for silver are more scattered, but the shock data agree with their estimate of the true value to 1 per cent for the modulus and 15 per cent for its derivative. Agreement with piston-cylinder data is somewhat poorer in each case. A similar recent comparison by Ming and Manghnani [78M4] of shock, ultrasonic, and X-ray data for six transition metals shows agreement within about 1 per cent for modulus and 10 per cent for its pressure derivative. Sodium chloride is a material that has received considerable attention and the results of this work have been subjected to critical review by Birch [78B4].

3.3. Plastic and viscoplastic solids

3.3.1. Introduction

In this subsection we review observations of the response of solids to rapidly applied stresses in the range between the Hugoniot elastic limit and the value at which the elastic precursor wave is overtaken by the plastic wave. In this regime a shock evolves into a structured wave similar to the ideal elastic-plastic profile of fig. 2.2d, but differing from it in ways that reveal information about the mechanisms of rapid inelastic deformation, as indicated in fig. 3.3. Waveform measurements carried through to the decompression phase and those arising from the introduction of a sequence of shocks into a sample provide data on the shear strength of solids and permit some assessment of the limits of validity of the hydrodynamic approximation. Much of the technological interest in shock compression of solids centers on elastic-plastic phenomena.

The unique features of shock-loading experiments are that measurements of plastic flow can be made in precisely-controlled states of uniaxial strain and at strain rates that are higher than those achieved by most other means. The discussion of this section relates primarily to observations involving sufficiently low compressions that effects of shock heating and nonlinear elastic response are small. Investigations to determine material response have concentrated on four different features of the problem: (1) the elastic precursor to the plastic wave, (2) the profile of the plastic wave, (3) the profile of the decompression wave, and (4) the response of shock-compressed matter to the introduction of additional compression waves.

The first report of measurement of wavespeeds in a shock-loaded solid was that of Pack et al. [48P1], while the earliest experimental measurements permitting resolution of an elastic-plastic wave profile were made by Minshall [55M2]. Detailed continuum-theoretical analysis was begun by Wood [52W1] and continued by Morland [59M1] and Fowles [61F2], who also obtained the first experimental results confirming, in a general way, the predictions of the ideal elastic-plastic model. With improved instrumentation, wave profiles in metals were examined by Butcher and Canon [64B5], Barker et al. [64B1], Butcher and Munson [65B5], Novikov et al. [66N1], Butcher and Karnes [66B4], and others. This work demonstrated the existence of strain-hardening and viscoplastic effects and represented an attempt to incorporate them into a mechanical theory. During this same period, Jones and coworkers [62J2, 64J1] measured Hugoniot elastic limits of a number of metals and found many in substantial disagreement with predictions based on a rate-

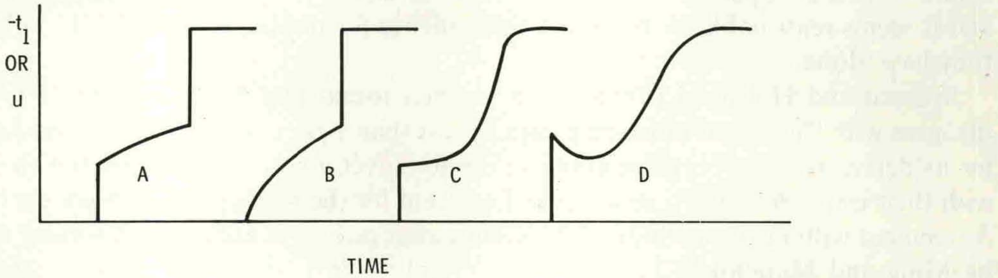

Fig. 3.3. Deviations from ideal elastic-plastic response often lead to variants of the waveforms shown. In example (A) an increase in shear strength during the early stages of the inelastic deformation is indicated, an effect usually described as "strain hardening". The waveform of example (B) is interpretable as involving either large strain hardening following a very weak wavefront or, more plausibly, as some form of gradual yielding. The dispersed plastic ave of example (C) is usually taken as evidence of viscoplastic flow, while example (D) represents the viscoplastic response observed in high-quality monocrystals.