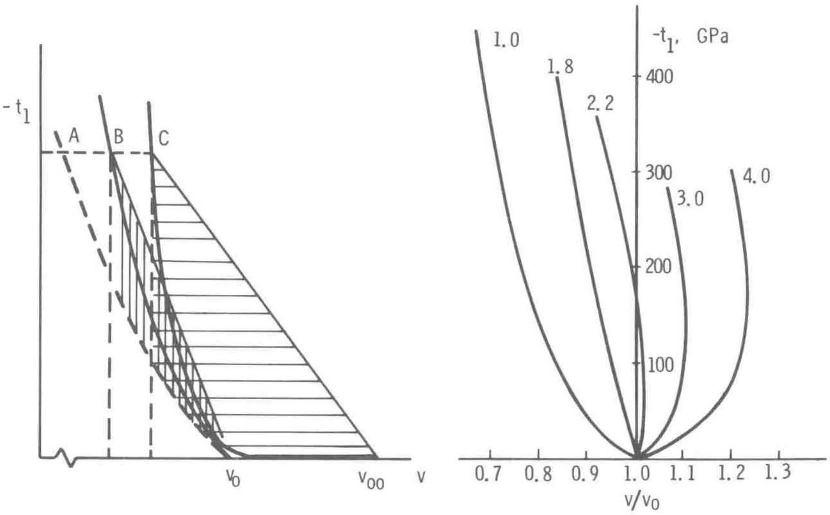

(a) (b)

Fig. 3.2. The internal energy imparted to material by shock compression corresponds to the area under the Rayleigh line. The thermal energy is represented by the shaded portion of this area between the Rayleigh line and the cold-compression curve (A), in part (a) of the figure. For shock compression to a given stress, this thermal energy is much greater for material that was initially distended to a specific volume v_{00} (Hugoniot curve C) than for material compressed from its normal specific volume v_0 state (Hugoniot curve B). The additional energy is almost entirely thermal, and gives rise to thermal pressures sufficient to produce the widely separated Hugoniot curves shown for various distention ratios v_{00}/v_0 in part (b) of the figure (plotted from data of Krupnikov [62K 2]).

3.2.3. Multiple-shock compression

A second method of obtaining the additional (p, v, ε) data required for thermodynamic studies involves subjecting the sample to successive shocks. This leaves it in a state that can be determined experimentally and which is different from one on the principal Hugoniot curve. This method has been used by Walsh and Rice [57W1, 57R1] to determine the equation of state of water, and by Al'tshuler and Petrunin [61A2], van Thiel et al. [66V1, 74V1], Al'tshuler and Pavlovskii [71A5], Neal [77N1, 79N2], Nellis et al. [78N1] and others to study several other materials. Some experiments involving Mach reflections have been conducted by Al'tshuler et al. [62A2], Leygonie and Bergon [68L1], and Neal [75N1, 76N1]. It is only in the most recent of this latter work that practical results are being obtained, but the method shows promise.

When a substance is compressed to a given density by multiple shocks rather than a single shock of greater strength, the compression is achieved with a smaller increase in entropy and temperature so this experiment provides access to states of higher density than the principal Hugoniot state at the same pressure.

Studies of the propagation of weak disturbances into shock-compressed material provide additional information about the material in its compressed state and are necessary to assess the errors implicit in the hydrodynamic approximation. Consideration of this matter must await the next section on elastic-plastic response, however, because the response of the material to these weak disturbances is often that of a solid, not a fluid.

3.2.4. Compressible fluid approximation to the high-pressure equation of state of solids

A basic application of Hugoniot data is to the thermodynamic characterization of materials at high pressure and temperature. The development of an equation of state based on shock-compression data rests on the assumption that these data represent an equilibrium thermodynamic state in which the pressure and internal energy are functions of the variables v (or ρ) and s (or θ).

In the absence of any specific evidence to the contrary, it is assumed that experimental data refer to states of equilibrium. In some cases a transformation to a dense phase may proceed so slowly that the measurements refer to "metastable" properties of the low-density phase. The treatment of melting is uncertain since its effect on Hugoniot data, particularly when it occurs at high pressure, is usually so small as to escape detection [66U1, 71M2, 75A3].

The question of whether or not the state achieved by shock compression is adequately described by the usual thermodynamic variables is more troublesome. It is necessary, of course, that effects of shear strain be negligible, or that the measured stress component t_1 and internal energy density ε be corrected to yield the associated pressure p and compression energy. It is also necessary that the defect structure in the lattice be in equilibrium, that it not vary with compression, or that the changes that do occur have negligible effect. Shock compression is known to produce profound changes in the defect structure of solids, but the effect of these changes on thermodynamic properties of the compressed solid has not been investigated in detail. Zharkov and Kalinin [71Z2] have estimated the increase in pressure attributable to the presence of lattice vacancies and found it to be negligible for equilibrium concentrations. Concentrations orders of magnitude greater than thermal-equilibrium values have been found by metallurgical examination of material recovered after shock compression, however (see section 3.6), and a proportionate increase in their effect would produce a large pressure correction. Electrical resistivity data (see section 4.10) provide evidence for vacancy concentrations sufficient to contribute several per cent to the total pressure. The effect of these and other shock-induced defects on equations of state deduced from shock-compression measurements is a basic issue requiring further study.

In some cases yielding has been shown to proceed heterogeneously (see section 3.4), and there is reason to believe that this situation becomes increasingly common as the shock strength is increased. The formation of deformation bands is an extreme example of defect production and presents a case where thermal inhomogeneities are obviously present and where the measured properties must be those of a mixture of the material in various states. That it seems not to be noticeable in comparison of shock-compression and other pressure-volume data may be due to the insensitivity of the measurement or may indicate that the deformation bands are of sufficiently fine structure that they reach thermal equilibrium in times negligible relative to the duration of a typical experiment.

All of the effects discussed result from shear stresses. This and other evidence confirms their existence at the highest pressure where they have been sought, certainly to 100 GPa in several metals. These stresses produce significant mechanical effects of both qualitative and quantitative nature at pressures where they have been studied. The thermodynamic contribution of the distortional energy is small [73D5] and the same seems to be true for other effects, although their contribution has not been carefully assessed.

One must not infer from the foregoing remarks that shock compression produces a state of complete disorder in a crystal. The most direct evidence for retention of crystalline order comes from flash X-ray diffraction patterns obtained from material in the shock-compressed state. The technique for obtaining these patterns is still under development, and the interpretation is a subject of some discussion, but useful results have been obtained by Johnson et al. [72J4], Egorov et al. [72E1], Müller and Schulte [78M11], Kondo et al. [79K3], and Jamet and Bauer [78J1]. These investigators find that crystalline order is retained in a variety of solids. The considerable line broadening observed is taken as a measure of defect or mosaic structures formed.