aggregates, with this fraction rising to 80 per cent at the higher stress. Examination by field-ion microscopy showed that only a very small proportion of the vacancies had coalesced to form these loops, with the remainder being present as monovacancies or small aggregates. The total vacancy concentration increased from an apparent background of 1.2 per cent (including artifacts) to 6 per cent after 25 GPa shock.

Early investigations disclosed shock compression as a particularly effective means of hardening metals, with roughly linear increases in indentation hardness with shock stress being observed in a variety of metals [63D3]. Shock hardening has since been observed to vary with stress pulse duration for pulses shorter than about 1 μs, but to be insensitive to variations in duration of the longer pulses that have been used for most work [78M7]. Hardening mechanisms vary from one material to another, and with changes in the strain history to which a given material is subjected. All of the defect structures observed have been implicated in hardening on at least some occasions. The stress-pulse dependence observed suggests that the mechanisms primarily responsible for the hardening operate rapidly and an investigation involving pulse durations as short as 4 ns has been undertaken by Mikkola and coworkers [78L1, 78W4] on Cu-8.6 per cent Ge. They find that, in the regime of short pulse durations, the hardening does not increase monotonically with duration as might be expected, but the observations remain to be explained.

Summary comments on recovery observations relate to the validity and interpretation of the experiments themselves and to the relation of this work to other aspects of the more general subject under review. Beginning with the first point, we note that much of the work has been done using inadequate recovery fixtures and poorly characterized loading histories. Much careful and sophisticated metallurgical work has been compromised by these deficiencies.

In early investigations, data were interpreted in terms of the peak compressive stress to which the samples were subjected, but both recent experimental work and theoretical considerations show that the duration of the stress pulse is equally important. Not all relevant parameters are subject to independent control since compression normally occurs more quickly in high-stress experiments than in those involving lower peak stresses and, of course, these experiments involve higher temperatures as well. The time required for the decompression process increases with both the peak stress achieved and the duration of its application, and observations or suggestions that various residual microstructures (e.g., twins) develop during this phase makes this correlation significant. The issue of conditions under which various defect structures form, and the rate of their development, deserves serious attention.

Much of the disagreement among observations cited by Leslie [73L1] now seems to stem from variations in loading history and such features of initial sample microstructure as grain size. No investigation can be interpreted with confidence in the absence of detailed knowledge of these matters. The complexity of observed behaviors and terminal microstructure also necessitates a rather comprehensive characterization of residual properties.

The recent trend toward more quantitative reporting of microstructural observations is encouraging and must continue if this work is to be related to other aspects of the study of shock-compression phenomena.

Dislocations and twins have been discussed in a rather idealized way in connection with the considerations of plastic deformation in section 3.3. The present discussion is not unrelated, but no precise connection has been made between the continuum version of the concepts and the more realistic versions encountered in recovery observations. These observations do confirm dislocation motion and twinning as important deformation mechanisms, but the complexity of

deformation phenomena is also disclosed with observation of deformation band structures, formation of dislocation cells, grain rotation, effects of phase instability in alloys, etc., all being involved in various contexts. It seems clear that the influence of these phenomena on observed wave profiles must be assessed and, as necessary, incorporated into mechanical constitutive equations. The fact that a variety of residual effects appears to depend on the duration of the period for which the sample is under compression indicates that the assumption that the compressed material is in a state of equilibrium at a point on its yield surface stands in need of some reevaluation.

The discussion of this section has been limited to metals, but shock-induced defects are found in other substances as well (see, e.g., the observations of MgO by Klein and coworkers [64G1, 65K3, 66K2, 66K3]), and may be expected to have equally significant effects on their mechanical, electrical, and optical behavior.

Shock-induced defects must be given special consideration in interpretation of other observations because they are usually present in much larger concentration than in samples subject to similar deformation by static means, and occasionally take forms not normally found in statically deformed material. The shock loading environment presents unique problems of interpretation of defect-sensitive phenomena.

3.7. Material synthesis

Polymorphic phase transitions are readily induced by shock compression (see, e.g., [77D6]), and it is of considerable interest to obtain samples of dense phases for scientific studies and for technological applications. Unfortunately, few materials remain in their high-pressure phases after decompression, and it is unusual to recover them in other than trace amounts. Nevertheless, there are some notable exceptions: dense boron nitride is recovered with good yield from graphitic boron nitride, diamond is recovered with good yield from shock-loaded graphite and yields as large as 90 per cent are reported for a dense orthorhombic form of TiO_2 obtained from shock-loaded rutile. There are also a few isolated cases of dense phase recovery in AlN [69V2], Ti [70G1], Zr [70G], Se [77D2], yellow and red phosphorus [58G1], bcc Fe-Ni alloys [68R2, 65L1], plagioclase [63M1], Fe-Ni-Cr alloys [60D1], and cobalt [57L1].

Unfortunately, there are no systematic attempts to explore *failure to recover* dense phases, but such failures are reported for iron [64M1], most iron alloys [61F1], Ge [65K1], Si [65K1], CdS [65K1], InSb [65K1], CdSe [65K1], NaCl [69B2], and $LiNbO_3$ [79S2]. Some of these reported failures may be due to insufficient effort since identification of trace amounts requires skill and persistence; for example, DeCarli's identification of diamond and stishovite in shock-loaded samples required considerable persistence along with special chemical processing and concentration.

The considerable geophysical work on changes in defects and structure produced by natural and laboratory shock loading of rocks and minerals has recently been thoroughly reviewed [72S4] and need not be discussed here. Diamond synthesis is routine with static-high-pressure techniques [77B2] and static high pressures are routinely used to aid the synthesis of other single crystals [77W1].

Much of the early material synthesis work was performed on samples close to solid density, whose full composition was the material to be transformed. This approach limits both the temperature and pressure achieved and gives no control over the local temperature history of the materials.