conditions are significantly time dependent. Such gross deviation from equilibrium behavior as a result of yielding leads to a situation in which critical thermodynamic variables are controlled by the yield process rather than by the nominal conditions of uniform temperature and pressure. The effect of such a situation is well demonstrated in quartz in which recovery experiments indicate higher concentrations of dense phases, stishovite and coesite, along regions that have experienced localized melting (see section 3.7). Furthermore, the anomalous metastable mixed phase region observed in quartz may be a consequence of such heterogeneous processes. This view is strengthened by the recent observation of a similar extended mixed phase region above the phase transition initiated in $LiNbO_3$ at 15 GPa [79S2]. It is also apparent that in strong solids of low thermal conductivity, the sample is no longer in its virgin state and changes induced by such yielding must be explicitly considered in interpretation of experimental results. Grady [78G2] has recently developed more explicit models for the thermodynamic consequences of shock-induced phase transitions on heterogeneous yielding.

3.5. Spall fracture

A *spall* is a material fracture produced by the action of tensile stress developed in the interior of a solid body when two decompression waves collide. Spalls result from impact, detonation of contacting explosive, contact with an electrically-exploded wire or foil, deposition of intense pulses of radiation produced by electron beam accelerators or lasers, and other causes. Knowledge of spall phenomena is important in military applications, for the design of explosive metal-working processes, and to ensure that it does not occur inadvertently during other shock experiments. Fracture processes can be construed as deformation mechanisms and, as such, must be included in comprehensive theories of the mechanical behavior of solids. Finally, spall experiments have begun to take their place among other means of scientific investigation of fracture processes. A natural extension of investigations of spallation is to the study of dynamic fragmentation processes, a topic now being pursued for its application to mining operations [73S2, 74S3].

Early investigators, using explosive systems to introduce stress waves into their samples, attempted to determine conditions of stress, duration of stress application, etc., under which a spall would occur and to investigate various metallurgical aspects of the spall process. Much of this early work has been reviewed by Butcher et al. [64B4]. The experimental method offering the greatest control over the variables of importance to spallation involves impacting a target plate made of the sample material by a thinner impactor plate of the same material that has been accelerated to the desired velocity using a gun. The magnitude and duration of the tensile stress pulse produced in this experiment is controlled by varying the impact velocity and the thickness of the impactor plate, respectively.

The material response to brief application of tensile stress is frequently the development of a diffuse distribution of small cracks or voids in the material. For stress pulses of sufficient amplitude and duration, this damage may accumulate to the point where the sample fractures completely. The tensile stress required to produce some given level of damage (however this may be defined) is called the *spall strength*. Since an increase in either the tensile stress or the duration of its application increases the amount of damage produced, the spall strength of a material varies with both the degree of damage taken to constitute a spall and the duration of the tensile stress pulse.

A number of investigations in which plate-impact experiments were conducted to provide quantitative information at low-to-moderate damage levels are summarized in table 3.6. Most of these investigations have had as their objective the determination of conditions under which damage is produced in structural materials.

Spall damage develops in stages dominated by (1) the nucleation of cracks or voids or the activation of growth at existing damage sites, (2) growth of individual fracture nuclei, and (3) coalescence of neighboring cracks or voids. The process may be arrested at any point of its course.

Nucleation of spall damage. Spall damage can develop at material defects such as grain boundaries, inclusions, microcracks, etc., or at sites at which no defect is apparent upon metallographic examination [73S3]. The nature of fracture nuclei when no obvious defect is present has been a subject of speculation for many years. Attempts have been made to identify them with various atomic-scale defects such as dislocation pile-ups or to assume they arise as a normal consequence of thermal motion of the lattice. Neither these nor other microscopic models have been subjected to critical test in spall experiments because they deal with phenomena occurring below the level at which observations have been made. Occasional observations such as one by Seaman et al. [71S1] on annealed, high-purity polycrystalline aluminum suggest a nucleation mechanism related to the dislocation substructure within individual grains. Galbraith and Murr [75G1] and Murr [76M5] have suggested that nucleation at grain boundaries in beryllium and molybdenum may be controlled by dislocations and ledge structures present there. Even if fundamental damage-nucleation mechanisms are operative, however, they may be dominated by effects of gross pre-existing flaws. Most research on spallation has been related to technical materials and, in the overwhelming majority of cases, damage has been observed to form at sites of gross defects. It is clear that even material samples of rather high perfection contain defects in sufficient quantity to account for the observed concentrations of damage sites, and the defect concentration can be expected to increase significantly in the compression phase of the stress history that precedes development of a spall. Stevens and Tuler [71S2] found that this precompression history had no effect in mild steel or aluminum alloy 6061-T6, but an effect might be expected in more nearly perfect materials. Spall experiments designed to explore nucleation phenomena in materials of high perfection seem useful in arriving at a basic understanding of fracture phenomena generally, but few suitable experiments have been conducted and none have been interpreted in terms of basic nucleation models.

If we accept the premise that damage develops at flaws inherent in the material, then the issue becomes one of activation rather than nucleation. Explaining the activation of ductile growth of voids seems not to present a problem as the stress thresholds above which voids have been observed to develop exceed the elastic limit of the material in question. The case of plane cracks is more interesting, and one having a long history. The issue as it relates to spallation has recently been investigated by Kalthoff and Shockey [77K1]. They found that the onset of growth of cracks (in this case rather large ones) in a polycarbonate plastic is interpretable in terms of a generalization of concepts of static fracture mechanics. This generalization includes the use of a dynamic value for the critical stress-intensity factor and a requirement that the stress intensity be maintained for a minimum time. If this or some similar model can be shown to apply in sufficient generality, and if damage develops primarily at pre-existing cracks, then the nucleation phase of the spall process would be replaced by an activation phase. Some, as yet unstudied, intermediate conditions can be expected to prevail when damage is initiated at the grain boundaries, inclusions, etc., present in technical metals.

Growth of spall damage. In homogeneous material, damage takes the rather distinct forms of voids produced by plastic flow or cracks produced by cleavage. An example of ductile void growth