# Phase transitions under shock-wave loading*

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First-order polymorphic, second-order, melting, and freezing transitions induced by shock-wave loading are reviewed. Comprehensive tabulations of the experimental observations are presented and materials that have been subjected to in-depth study are reviewed in more detail. Theories of the mechanics, thermodynamics, kinetics, and shear strength of shock-loaded materials are described and experimental techniques are briefly reviewed.

## CONTENTS

## I. INTRODUCTION

Shock phenomena most commonly experienced by an individual are the boom from supersonic aircraft, the crack of a rifle, and automobile pileups on crowded freeways. The fact that the last-named event produces a shock wave suggests what is indeed true: that shock waves are very general and are, if not ubiquitous, at least pervasive. Extensive use has been made of the shock wave as a scientific tool in the study of gases, but there has been limited application to solids. Even so, considerable data have accumulated in the last twenty years on miscellaneous problems, even though there has not yet been concentrated study of many subjects. One area which has received considerable attention is the pressure-induced phase transition. Testimony to this attention lies in the entries of Table AI of the Appendix. Even here, however, efforts are in general fragmented, and few materials have been studied in detail compared to static high-pressure investigations. (See, for example, Klement and Jayaraman, 1967 and Rooymans, 1969.)

The purposes of this review are to present some elementary things about shock waves, to explain how they relate to phase transitions, to tell what measurements can be made and how, to list and discuss measurements that have been made, and to point out some areas for future work.

Shock waves in solids are ordinarily produced by impact of a projectile on the sample or by detonation of an explosive in contact with it. In either case, the result is the introduction of a step pressure that propagates through the sample, changing shape as it goes; these changes in shape result from the action of inertial forces derived from mechanical properties of the sample. When shock waves are used to probe material properties, the challenge to the experimenter is to accurately measure changes in shock-wave shape and to interpret them in terms of material properties. The philosophy is analogous to that involved when response of an electrical network to a step in voltage is used to determine network parameters. But the shock-wave problem is more complicated because the sample is a continuum and because relations between impressed force and mechanical response are nonlinear.

A stress pulse produced by sudden application and

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subsequent release of pressure on the surface of a solid has a beginning, a middle, and an end. The beginning is a shock front, i.e., a near-discontinuous compression. The middle is a region of uniform or slowly varying pressure, density, and temperature; the end is a rarefaction that returns the material to something approaching its original state. In some experiments the middle region is so abbreviated that only beginning and end are apparent. A representation of an unusually complicated pressure profile is shown in Fig. 1. All these features, developing from a step in pressure loading and a subsequent unloading applied at a plane boundary, may exist in a single sample, but are not apt to be recorded in a single measurement. $\mathcal{S}_1$ is an elastic shock travelling at the dilatational wave velocity and limited in amplitude by the shear strength of the material. In an ideal elastic–plastic solid, $\mathcal{S}_1$ brings the material to the point of permanent deformation, but no deformation occurs until $\mathcal{S}_2$ arrives. The second shock $\mathcal{S}_2$ is a wave of plastic deformation, often called the "Plastic I Wave," limited in amplitude by the pressure at which the phase transformation takes place. In a reversible transformation, $\mathcal{S}_2$ compresses the material to the boundary of the mixed phase region, but transformation is delayed until arrival of $\mathcal{S}_3$, the "Plastic II Wave." Transformation occurs in the shock front $\mathcal{S}_3$, going to completion if the driving pressure is large enough. The amplitude of $\mathcal{S}_3$ is determined by driving pressure. $\mathcal{S}_3$ travels more slowly than $\mathcal{S}_2$, which, in turn, travels more slowly than $\mathcal{S}_1$. In real materials the regions bounded by $\mathcal{S}_1$, $\mathcal{S}_2$, and $\mathcal{S}_3$ are regions of relaxation toward equilibrium. Immediately following $\mathcal{S}_3$ is a "rarefaction fan" $\mathcal{R}_1$. $\mathcal{R}_2$ is a "rarefaction shock," associated with the phase transformation which separated $\mathcal{S}_2$ and $\mathcal{S}_3$. Another nominally uniform region follows $\mathcal{R}_2$ and is bounded by the final rarefaction fan $\mathcal{R}_3$.

A shock wave results from inertial response of the material to sudden changes in pressure or particle velocity at a boundary. Pressures in laboratory shock experiments commonly range from about $10^9$ to $10^{11}$ Pa.[1] Measurements have been made at pressures as small as $10^7$ Pa and as great as $3 \times 10^{12}$ Pa. The latter measurement was made near an underground nuclear explosion (Al'tshuler *et al.*, 1968a). Duration of the high-pressure state produced by a shock wave is determined by characteristic dimensions that commonly range from 1 to 50 cm in diameter, corresponding to durations of about 0.5 to 25 $\mu$s. Most quantitative experiments are performed with plane-wave loading.

The possibility that phase transformations might be induced by shock waves was suggested at least as early as 1941 (Schardin, 1941), but the first serious experimental study of the subject was stimulated by an apparent anomaly in shock-wave compression of iron at high and low pressures (Bancroft *et al.*, 1956), arising from a phase transition at 13 GPa.

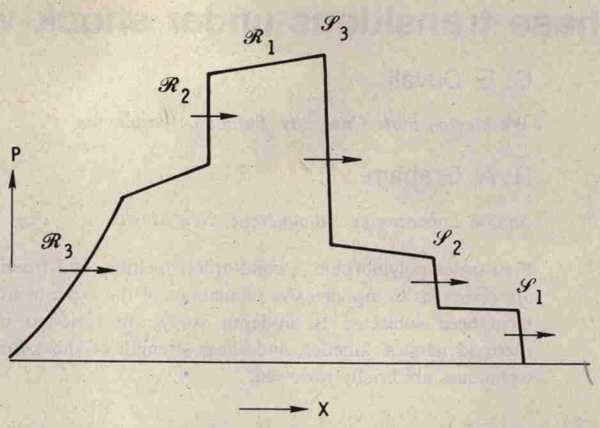

FIG. 1. Pressure distribution in a pulse propagating through a material undergoing a phase transformation and a transition from elastic to inelastic behavior.

Discovery of the 13 GPa polymorphic transition was a notable scientific achievement. Since the transition had not been observed before, unique capabilities of shock-wave experimentation were clearly demonstrated. This discovery stimulated further static high-pressure research and has played a major role in establishing a pressure calibration scale for static experiments. Shock experiments by Johnson *et al.* (1962) gave the first evidence for a triple point in the pressure–temperature phase diagram of iron. Detection of the well-known Bi I → Bi II transition under shock loading by Duff and Minshall (1957) confirmed the importance of shock loading experimentation in the study of polymorphic phase transitions.

Shock-induced polymorphic transitions are important for their applications. A particularly notable application is in material synthesis, exemplified by production of diamonds in shock-loaded graphite (DeCarli and Jamieson, 1961) and of cubic and wurtzite forms of BN from shock compression of hexagonal BN (Batsanov *et al.*, 1965; Coleburn and Forbes, 1968). Diamonds of industrial quality are now produced commercially by E. I. Dupont de Nemours Co. and Allied Chemical Corp. (Trueb, 1970, 1971). Scientists in the Soviet Union have undertaken an extensive program in material synthesis with shock loading techniques (Ruchkin *et al.*, 1968; Kirkinsky, 1968; Batsanov, 1968; Boreskov *et al.*, 1968; and Batsanov *et al.*, 1969). Material synthesis, not necessarily involving polymorphic phase transitions, includes polymerization (Al'tshuler *et al.*, 1968b; Adadurov *et al.*, 1965) and synthesis of superconducting intermetallic compounds (Barskii *et al.*, 1972; and Otto *et al.*, 1971). It has also been demonstrated that damage due to hypervelocity impact may be strongly influenced by phase transitions (Shockey *et al.*, 1975; Bertholf *et al.*, 1975). The possibility of producing metallic hydrogen in explosively driven magnetic compression experiments has been explored. (See, for example, *Physics Today*, Vol. 26, No. 3, p. 17, 1976).

Many measurements of shock transition pressure have now been reported. Many of them are isolated measurements that neither exploit nor illustrate the full capabilities of shock compression techniques. The novelty of shock-induced transition measurements has given way

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[1] One pascal equals one newton/meter$^2$ or 10 dynes/cm$^2$. Multiples of the pascal used here are the terapascal (TPa), gigapascal (GPa), and the megapascal (MPa), which are equal to $10^{12}$, $10^9$, and $10^6$ newtons/meter$^2$, respectively. One GPa = 10 kilobars or about 10 000 atmospheres.