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Introduction

Dynamic compression is a nonlinear process that achieves extreme pressure P, density ρ, internal energy E and temperature T via a supersonic compressional wave. Because compression is so fast, temperature and entropy S are generated simultaneously under adiabatic compression within the front of the supersonic matter wave. Thermodynamic states achieved are tunable over wide limits by choice of the temporal history of the pressure pulse that generates the compression. Magnitudes of thermodynamic states are determined by the magnitude of energy coupled into a material in the process.

Pressure is defined herein to be dynamic if its rate of application affects induced T and S and the compression is adiabatic. Supersonic adiabatic compression significantly affects T and S. In contrast "slow" sonic (isentropic) compression is reversible by definition and its rate of application has relatively small affect on T. Static compression is sufficiently slow that heat is transported out of a sample essentially as it is produced by compression and thus is isothermal and non-adiabatic.

Supersonic hydrodynamic shock flow in a fluid generates a matter wave, whose front is a jump in pressure and associated thermodynamic variables from a lower-pressure state ahead of the front of the wave to a higher-pressure state behind the wave front. Because shock flow is supersonic, material ahead of the shock wave in a fluid does not receive a precursor signal prior to arrival of that wave. Thus, a supersonic wave "snow plows" a fluid, which rapidly compresses, heats and disorders matter upon thermally equilibrating to final pressure behind the wave front. The front of a shock wave in a fluid is the non-equilibrium region in which a shocked fluid equilibrates thermally upon going from the lower-pressure to the higher-pressure states.

Historically, dynamic compression (DC) has been achieved primarily with a single, sharp, step-increase in pressure, which in a condensed fluid has negligible rise time (~ps) over a thin (~nm) wave front. Such a wave is commonly known as a

shock wave in condensed matter. Dynamic compression is not restricted to a Heaviside-type step-jump of shock pressure, as is often thought. Probably the most important advance in dynamic compression in recent years is recognition of the fact that the pulse driving the compression is not restricted to a shock wave. This recognition has expanded significantly the range of thermodynamic states achieved dynamically, and with it the capability to address an expanded number of challenging problems over a wide range of pressures and temperatures.

A paradigm in this regard is the making of metallic fluid hydrogen (MFH), which has been a major goal of high-pressure experiments since the 1950s. MFH has been made by shaping applied dynamic pressure pulse to obtain quasi-isentropic compression with a multiple-shock wave consisting of ~10 small shocks to peak pressure. Such a wave achieves substantially lower temperatures, entropies and higher densities than compression with a single sharp shock. This technique made MFH degenerate at pressure 140 GPa (1.4 million bar) and 0.63 mol H/cm^3 (ninefold liquid-hydrogen density) (Weir et al., 1996a; Nellis et al., 1999), which is essentially the metallization density of H predicted by Wigner and Huntington (1935).

That metallization of monatomic fluid H was achieved by overlap of $1s^1$ electronic wave functions on adjacent H atoms in experiments with lifetimes of ~100 nanoseconds (ns) (Weir et al., 1996a; Pfaffenzeller and Hohl, 1997; Nellis, et al., 1998; Nellis et al., 1999; Fortov et al., 2003). The making of MFH under dynamic compression illustrates the importance of temperature for achieving a metallic fluid at a relatively low pressure and the broad potential of DC for addressing major long-standing scientific issues.

Bethe and Teller (1940) performed the first theoretical investigation of the nature of the front of a shock wave. That work of Bethe and Teller (BT) showed that the asymptotic values of material velocity, density, pressure and temperature at high pressures a sufficient distance from the front of the shock wave (Fig. 1.1) are determined by the values of those quantities at low pressures ahead of the traveling shock front, independent of microscopic non-equilibrium conditions within the shock front. That unpublished report of BT is considered to be a key paper in the study of solids far from equilibrium (Mermin and Ashcroft, 2006).

Spatial and temporal thicknesses of a 1.2 GPa shock front in compressible liquid Ar were calculated by Hoover (1979) and by Klimenko and Dremin (1979) using Navier-Stokes equations and molecular dynamics, respectively. As shown in Fig. 1.1, spatial and temporal thicknesses of that shock front are ~nm and ~ps, respectively, which are sufficiently fast to generate substantial temperature T and thermally equilibrated disorder S. Multiple-shock compression is a sequence of several discreet jumps each as in Fig. 1.1. Thermally equilibrated heat and disorder in the form of temperature T and entropy S distinguish fast (~ps) shock compression from slow (~s) isothermal static compression. The apparently smooth increase

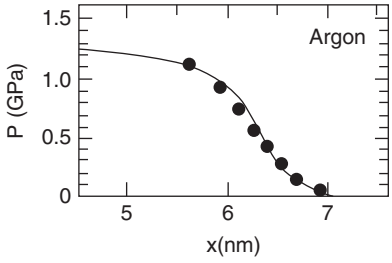

Fig. 1.1. Calculated rise to shock pressure of 1.2 GPa in shock front of liquid Ar. Full curve calculated with atomistic molecular dynamics (Klimenko and Dremin, 1979); solid circles calculated with Navier-Stokes equations (Hoover, 1979). Shock speed u_s is 1.8 km/s; rise time from 0 to 1.2 GPa is ~10^{-12} s over ~nm shock front thickness. Copyright 1979 by American Physical Society.

in pressure in Fig. 1.1 belies the fact that P and other calculated thermodynamic quantities were obtained by averaging computational results at various depths within the non-equilibrium shock front.

In the 1970s and 1980s, shock research was broadened to achieve quasi-isentropic compression by increasing the rise time of a shock wave. In planar geometry, ramp waves were generated experimentally with graded-density impactors (Barker and Hollenbach, 1974; Barker, 1984). A ramp wave is a pressure pulse that increases with time, generally linearly in practice. Multiple-shock waves were generated computationally using multiple layers of materials to break up a strong shock into numerous smaller ones (Lyzenga and Ahrens, 1982). Dynamic compression is achieved by a general pressure pulse shape, of which shock, multiple-shock and ramp-compression waves are three types. Because the rate of application of dynamic pressure P can readily be tuned experimentally, T, S, ρ and E are tunable over significant ranges by choice of applied pressure pulse $P(t)$, where t is time.

Dynamic compression is a mature field of hydrodynamics with its mathematical origins in European universities in the last half of the nineteenth century (Courant and Friedrichs, 1948). In the nineteenth century, what is known today as dynamic compression was probably known as supersonic hydrodynamics. The existence of dynamic compression might well have been forgotten with development of quantum mechanics in the 1920s, but for defense research initiated in the 1930s prior to World War II (Bethe and Teller, 1940). In the 1940s, funding appeared for national facilities to perform experimental shock-compression research to complement theoretical research performed between ~1850 and ~1910 (Chapter 4). Shock-compression research eventually morphed into dynamic compression. The purpose of this book is to provide a primer on the basic ideas of dynamic compression and to discuss recent achievements that illustrate its broad potential.

1.1 Beyond Shock Compression: Tunable Thermodynamics

In 1935, Wigner and Huntington (WH) predicted that at some high pressure greater than 25 GPa (0.25 Mbar), a density of 0.62 mol H/cm^3 and very low temperatures, electrically insulating solid H_2 would undergo a first-order transition to metallic H. Stewart (1956) made solid H_2 at the then "high" static pressure of 2 GPa, which generated interest in the static-pressure community to look for solid metallic H at much higher pressures. In the 1990s, MFH was made by specifically tuning thermodynamic conditions in liquid hydrogen by dynamic compression to dissociate liquid H_2 into fluid H at sufficiently high densities and low temperatures to make electrically conducting monatomic fluid H at sufficiently low temperatures to make degenerate fluid H.

Thermodynamics are tuned by tuning supersonic hydrodynamics. The shape of a dynamic pressure pulse and associated shock-induced dissipation were used to tune states off a shock-compression curve, which is commonly known as a Hugoniot or Rankine-Hugoniot curve. A shock-compression curve is a locus of states achieved adiabatically with a sequence of single, sharp shock compressions of increasing shock pressures. Because dynamic temperatures T are relatively high herein, S produced by dynamic compression is usually considered to be thermally equilibrated disorder. Because Helmholtz free energy F is given by $F = E - TS$, dissipation energy $E_d = TS$ is used to tune phase stability. In a given process S is maximized to minimize H at a given T.

In the 1990s, the H_2 vibron (diatomic vibrational frequency) was observed in the insulating solid at static pressures up to ~300 GPa. The H_2 molecule in the solid is extremely stable under pressure. WH had anticipated the possibility that their predicted simple dissociative transition might not occur and speculated on what else might happen instead at some very high pressure (Wigner and Huntington, 1935). By the early 1990s, metallic solid H had yet to be made under static compression, and dynamic compression was beginning to look attractive as a potential alternative tool to make metallic hydrogen by tuning dissipation S and T. The challenge was to find an appropriate pressure profile that would generate sufficient thermal energy and entropy via dissociation of H_2 to H at sufficiently high ρ and sufficiently low T to make degenerate metallic H.

The discipline of dynamic compression began when W. J. M. Rankine (1870), a professor at the University of Glasgow, published conservation equations of momentum, mass and internal energy across the front of a shock wave. Rankine explicitly used the equation of state (EOS) of an ideal gas, whose derivation had then been completed relatively recently in the sense that W. Thomson, Lord Kelvin, also of the University of Glasgow, had derived absolute 0 K on the Centigrade temperature scale (Thomson, 1848). H. Hugoniot was captain at the

Marine Artillery Academy of France and subsequently derived those conservation equations on a more general basis (Hugoniot, 1887, 1889; Cheret, 1992).

Conservation equations for P, V and E across the front of a shock wave are called the Rankine-Hugoniot (R-H) equations or simply the Hugoniot equations. The locus of states measured under shock compression is commonly called a Rankine-Hugoniot (R-H) curve, a Hugoniot or a shock adiabat. Experiments to measure values of (P_H, V_H and E_H) are called Hugoniot experiments, where P_H, V_H and E_H are values of P, V and E on the R-H curve. Dynamic compression in general is a subfield of Applied Mathematics (Liu, 1986).

A dynamic isentrope is the limit of an infinite number of infinitely weak adiabatic shock compressions (Zeldovich and Raizer, 1966). Dynamic quasi-isentropic (Q-I) compression is essentially an isentrop plus sufficient S and T to achieve significantly higher densities and lower temperatures than achievable with shock compression, and thus might drive dissociation of H_2 and induce metallization of H. Multiple-shock compression is quasi-isentropic – typically an initial relatively weak shock followed by sufficiently many relatively weak shocks that lie on the isentrope starting from the first shock state, as for an ideal gas (Nellis, 2006a).

Ramp compression is achieved by a continuous adiabatic increase in dynamic pressure, rather than a sequence of relatively small discreet step-increases in pressure, as in multiple-shock compression. Dissipation in ramp compression can be tuned by the magnitude of the initial shock and temporal slope of the ramp. The smaller the initial shock and the slower the increase with time of the ramp, the lower the final temperature achieved. Multiple-shock and ramp compressions are essentially equivalent in the sense they can be tuned to obtain similar states.

Fig. 1.2 shows pulses achieved by a single shock to a given pressure and by multiple shocks to the same pressure. Fig. 1.2 illustrates that increasing the number of shocks to a given pressure is equivalent to slowing down the rise time to that given pressure. Fig. 1.3 illustrates schematically the two curves in P-ρ space that correspond to the pressure histories in Fig. 1.2, plus the 0-K isotherm. P_H in

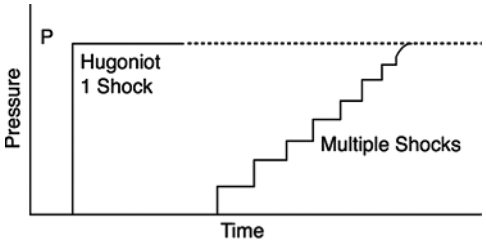

Fig. 1.2. Schematic of temporal pressure profiles for single- and multiple-shock compression to same pressure.

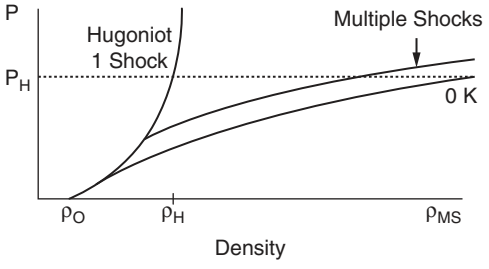

Fig. 1.3. Schematic in pressure-density space of single-shock (Hugoniot), multiple-shock (quasi-isentrope) and 0-K isotherm (static compression). P_H is P on Hugoniot at density ρ_H, which has limiting (maximum) shock density for given Hugoniot. ρ_{MS} is density achieved on multiple-shock compression to P_H. $\rho_{MS} > \rho_H$.

Fig. 1.3 is P on the Hugoniot at density ρ_H, which has a limiting (maximum) shock density for a given Hugoniot. ρ_{MS} is density achieved on a multiple-shock compression curve to pressure P_H. Fig. 1.3 shows $\rho_{MS} > \rho_H$. Extending the temporal interval of applied pressure history (Fig. 1.2) increases densities and decreases temperatures of thermodynamic states achieved by multiple-shock relative to single-shock compression.

If a material has internal degrees of freedom that can absorb shock-induced internal energy, then still lower Ts might be expected in addition to what would be produced hydrodynamically by multiple-shock compression alone. In the case of liquid H_2, dissipation energy is absorbed internally by dissociation of H_2 to H, producing entropy. This idea was successfully tested experimentally by producing metallic fluid H (Weir et al., 1996a; Nellis et al., 1999).

Ramp compression is a simple variation of multiple-shock compression, as illustrated in Fig. 1.4. A ramp-compression wave replaces discrete, numerous, weak, multiple shocks, as in Fig. 1.2, with a pressure that increases continuously from an initial weak shock pressure, say P_{H1}, up to maximum pressure P_{max}. Ramp compression is often a linear increase of pressure P with time. If $P_{H1} = 0$ and the ramp increase in P is sufficiently slow, then that ramp compression produces a dynamic isentrope. If $P_{H1} << P_{max}$ and the ramp increase in P is sufficiently slow, then that ramp compression is said to produce a quasi-isentrope.

1.2 Cold, Warm and Hot Matter

Ultracondensed matter herein is matter compressed by a factor ranging from ~1.5 to as much as 15-fold of initial sample density ρ_0 by pressures from ~50 GPa (0.05 TPa = 0.5 Mbar) to as much as a few TPa at relatively low temperatures T such that $T/T_F << 1$, where T_F is Fermi temperature of a Fermi-Dirac electron

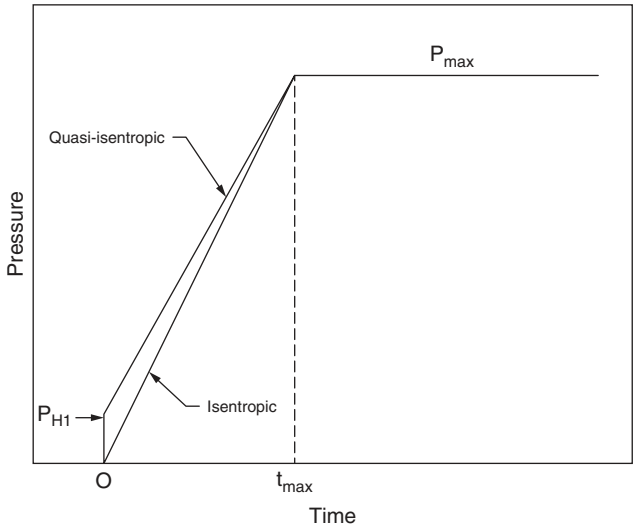

Fig. 1.4. Pressure histories for dynamic isentropic and quasi-isentropic compressions. t_{max} typically ranges from a few ns to ~100 ns (Nellis, 2006a).

system (Mott, 1936) and T/T_F is quantum degeneracy factor. T_F is defined at 0 K and depends on itinerant electron density. Absolute temperatures considered herein are typically in the range from 1000 K to tens of thousands of degrees Kelvin. Because ultracondensed compressions are large, T_F is also large. For this reason, ultracondensed degenerate matter is relatively straightforward to obtain, particularly for compressible materials. For example, MFH is made by dynamic compression at ~3000 K, ninefold atomic H density in liquid H_2 initially at 20 K and $T_F \approx 220{,}000$ K. Assuming total dissociation at that density, $T/T_F \approx 0.014 << 1$. MFH is "cold" at 3000 K because its metallization density ρ_{met} is so large and thus so is T_F.

While our chief interest is ultracondensed matter, dynamic compression can achieve high temperatures and degeneracy factors as well. In general, $T/T_F << 1$, $T/T_F \approx 1$ and $T/T_F >> 1$ for cold condensed matter, warm dense matter (WDM) and hot plasmas, respectively. Thus, while dynamic compression is a process of classical physics, states produced by dynamic compression span the quantum range from degenerate to highly non-degenerate.

A remarkable unexpected case of systematic behavior of warm dense fluid metals has been observed under shock pressures from 0.3 TPa up to 20 TPa (200 Mbar). Those extreme pressures were generated in proximity to underground nuclear explosions (Trunin, 1998) and discussed by Ozaki et al. (2016) and in Chapter 10. Estimated temperatures in those experiments range up to several hundred thousand degrees Kelvin – surprisingly large for such systematic behavior.

1.3 Experimental Timescales

Dynamic compression discussed herein is such that (1) the compression process is adiabatic and (2) the rate of application of pressure is sufficiently large that it affects temperatures and entropies achieved. That is, conditions achieved depend not only on the amount of energy deposited but also on the rate at which energy is deposited. Dynamic compression is adiabatic if insufficient time is available during experimental lifetime for heat transport at sonic speeds into or out of a sample under supersonic dynamic compression. This condition depends on wave speeds and sample dimensions.

For this reason, dynamic-compression experiments to measure material properties are generally performed in one-dimensional (1D) geometry, which enables thermodynamic conditions to be determined simply by supersonic hydrodynamics, independent of thermal transport. In this case thermodynamic states to determine physical properties are sensitive primarily to dynamic compression and pressure release in the direction parallel to supersonic wave propagation, commonly called the longitudinal direction. Simultaneously, pressure release and thermal losses at sonic velocities in the direction normal to the direction of supersonic compression can be virtually eliminated in a portion of sample volume. In this way, for example, a sample volume can be designed to have constant, uniform P, V, and T for a time called the experimental lifetime. To obtain such a state with a lifetime sufficiently long to make an accurate measurement with a given diagnostic resolution time, dynamic experiments must be designed for particular sample materials, sample holder geometries and dynamic waveforms.

Experimental timescales and sample thicknesses are determined by transit times of supersonic and sonic waves. An estimate of representative experimental lifetimes is obtained from the transit time across ~mm, which for Cu at sonic velocity, for example, means a transit time of ~200 ns (ns = 10^{-9} s). Transit times at supersonic velocities are smaller. Experimental lifetimes of dynamic experiments generally range from a few ns to a few hundred ns or more, depending on shock driver and pressure. Samples thicknesses range from a few μm (10^{-6} m) to ~few mm with sample surfaces made and inspected flat and parallel to ~μm or less depending on shock driver. Time resolution required for accurate measurements extends down to as small as ~10 ps (ps = 10^{-12} s) for fast laser-driven shock waves. Diagnostics with high time and spatial resolution, including tight control on synchronization and cross timing between triggering and diagnostic systems, are required for dynamic compression experiments. *Because of this fast timescale, thermal diffusion, mass diffusion, fluid turbulence and convection are generally negligible in experimental volumes diagnosed under adiabatic dynamic compression.*

1.4 Thermal Equilibrium

Compressible fluids and metals are generally in thermal equilibrium under dynamic compression. Atoms and molecules thermally equilibrate after sufficient energy is exchanged in a sufficiently large number of interatomic collisions. This process in fluids occurs within the front of a shock wave (Fig. 1.1), which produces thermally equilibrated matter in a time much less than the duration of the experiment.

To diagnose a thermally equilibrated state, a large number of inter-atomic collisions must occur within the resolution time of a diagnostic system. If diagnostic time resolution corresponds to more than ~10 collision times, the sample is probably in thermal equilibrium. Collision times are estimated by average interatomic distance divided by particle velocity, often assumed to be ideal-gas thermal velocity for estimation purposes. For MFH at 3000 K and ninefold H density, ns time resolution corresponds to ~10^4 proton-proton collisions, which means MFH is in thermal equilibrium. In contrast, if diagnostic time resolution is less than required to achieve thermal equilibrium, then the temporal approach to equilibrium might be observed.

In the case of materials with strong chemical bonds of a few eV, thermal equilibration depends on shock pressure, density, shock energy deposited, bond strengths and experimental life time. The lowest shock pressure in a strong oxide ($Gd_3Ga_5O_{12}$ (GGG)) at which thermal equilibrium has been observed to occur in a narrow shock front on the Hugoniot is 130 GPa (Zhou et al., 2015). Shocked GGG is in thermal equilibrium for $P_H > 130$ GPa. GGG is the only strong oxide to date for which the minimum P_H that rapidly induces thermal equilibrium has been determined experimentally, to the knowledge of this author.

While thermal equilibrium is not possible in all materials during experimental lifetime, neither is it essential in all dynamic experiments. In many strong materials, shock-induced *mechanical equilibrium* is often sufficient. Sapphire (single-crystal Al_2O_3) is used as anvil in multiple-shock experiments. In this case, shocked sapphire need only be in mechanical equilibrium so that reproducible multiple-shock states in fluid hydrogen are achieved, for example. In this case, the sample (liquid H_2) rapidly equilibrates thermally in the fluid phase, while sapphire equilibrates mechanically below $P_H \approx 130$ GPa and probably equilibrates thermally as well for $P_H > 130$ GPa, at which shocked sapphire becomes opaque (Urtiew, 1974).

An extensive body of experimental EOS data under extreme dynamic shock pressures has been measured (Marsh, 1980; Trunin, 1998, 2001). Those results are used to design dynamic experiments. Trunin's (2001) compendium of experimental data up to 20 TPa (200 million bar) is unique and extremely valuable for

learning systematic "universal" behavior of materials at extreme shock pressures from few 0.1 TPa up to 20 TPa (Chapter 10).

1.5 Recent Accomplishments

Dynamic compression achieves ultracondensed matter at extreme conditions, which offers opportunities to understand phenomena not understood previously and to discover new interesting phenomena in regimes studied little, if at all. Measured dynamic-compression data are relevant to physics, chemistry, materials science, geophysics, planetary science, exoplanets, astrophysics, Inertial Confinement Fusion (ICF), etc. Dynamic compression thrives on the creativity of its users, and its uses are limited only by the imaginations of its practitioners. The following sections provide examples in which dynamic compression has been used to address questions of long-standing scientific and technological interest and to point out opportunities for future research.

1.5.1 Metallic Fluid Hydrogen (MFH)

High-pressure researchers have long been motivated to make metallic hydrogen whose existence was predicted by Wigner and Huntington (1935). With the end of the Cold War in 1989, dynamic high-pressure researchers in defense laboratories started investigating the possibility of making MFH with dynamic high pressures, because at that time metallic hydrogen had yet to be made under static high pressures. Degenerate metallic hydrogen cannot not be made with single-shock compression, because shock-heating limits shock compression to a value too small to make metallic H by quantum-mechanical overlap of electronic wave functions on adjacent H atoms. Dissipation T and S tuned by time history of a pressure pulse applied to liquid H_2 made degenerate (metallic) fluid H by dissociation of H_2 to H at sufficiently high pressures and densities and low temperatures. While temperatures exceeded melting temperatures at those pressures, those temperatures were sufficiently low to produce degenerate metallic fluid H.

WH's predicted metallization density, 0.62 mol H/cm^3, corresponds to a static pressure of 73 GPa at 300 K (Loubeyre et al., 1996). Temperature and entropy generated by dynamic compression achieved at finite temperatures with a two-stage light-gas gun (2SG) drove a crossover via dissociation from H_2 to H which completes at 0.63 mol H/cm^3 (3.8×10^{23} H/cm^3) and 140 GPa to make degenerate MFH at 140 GPa, T = 3000 K, T_F = 220,000 K and $T/T_F \approx 0.014 << 1$. That crossover completes essentially at the density of metallization of the first-order insulator-metal transition predicted by WH (1935). MFH under dynamic compression was achieved by reverberating a shock wave in liquid H_2 contained between