LA-UR -91-1820

LA-UR--91-1820

DE91 013370

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: OVERDRIVEN SHOCKS IN SOLIDS AND LIQUIDS

AUTHOR(S): Duane C. Wallace

SUBMITTED TO: American Physical Society Topical Conference on Shock Compression in Condensed Matter (~~June~~ July 1991, Williamsburg, Virginia)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

MASTER

OVERDRIVEN SHOCKS IN SOLIDS AND LIQUIDS

Duane C. WALLACE

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

The structure of overdriven shocks in solids and liquids is analyzed in terms of the underlying physical concepts, without resorting to formal mathematics. Two dissipative processes are required for the existence of a steady-wave shock, namely plastic flow in a solid, or viscous flow in a liquid, and heat transport in either a solid or liquid. The first requirement is the analog of Rayleigh's theorem for gases, and the second requirement extends Rayleigh's findings. For metals, the shock analysis yields approximate plastic flow data at strainrates approaching $10^{12}s^{-1}$. The shock risetime in solid or liquid metals is predicted to decrease to around a picosecond, as the shock strength increases through the overdriven threshold.

1. INTRODUCTION

Some years ago, I carried out a formal theoretical analysis of the structure of overdriven shocks in solids and liquids.[1-3] Here, in response to popular request, I review that analysis, not in the original abstract mathematical terms, but in terms of the underlying physical concepts.

Our assumptions are that the shock is a single steady wave, that the material is capable of transporting heat, and that the material undergoes elastic-plastic response in the solid phase, and viscoelastic response in the liquid phase. The analysis is based on irreversible thermodynamics, which is valid for shocks up to a certain strength, that strength being several Mbar for metals. These underlying theoretical assumptions are discussed in more detail in several other papers.[4-6]

The Hugoniot is the thermodynamic locus of shocked states, as a function of shock strength. The Hugoniot jump conditions follow from conservation of mass, momentum, and energy, together with the assumptions that the initial and shocked states are thermodynamic equilibrium states, and that the shock is a steady wave. These conditions relate the compression ε, normal stress σ, and internal energy U, to the shock velocity D and the particle velocity u. With intial and Hugoniot states denoted by subscripts a and H, respectively, the jump conditions are

$$\varepsilon_H = u/D, \tag{1}$$

$$\sigma_H = \rho_a D^2 \varepsilon_H, \tag{2}$$

$$U_H - U_a = \frac{1}{2} D^2 \varepsilon_H, \tag{3}$$

where ρ is density.

2. SHOCK WAVE EXISTENCE THEOREMS

In uniaxial compression of an element of mass, the transverse boundaries are fixed, the applied normal stress σ reduces the thickness of the mass element, and the transverse stress $\sigma - 2\tau$ is determined by the material response (see Figure 1). The shear stress τ is positive in compression. In a solid or liquid, the shear stress drives plastic flow or viscous flow, respectively, and in either case the flow proceeds so as to reduce both τ and σ.

The compression is $\varepsilon = 1 - \rho_a/\rho$. From the steady-wave assumption, and from conservation of mass and momentum, it follows that the relation between normal stress and compression within the shock is a straight line, called the Rayleigh line, and given by

$$\sigma = \rho_a D^2 \varepsilon. \tag{4}$$

The Rayleigh line for an overdriven shock, and the Hugoniot curves for solid and liquid, are

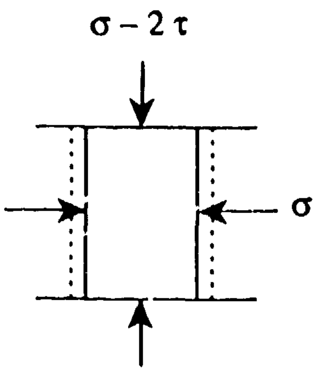

FIGURE 1
Deformation of a mass element in uniaxial compression.

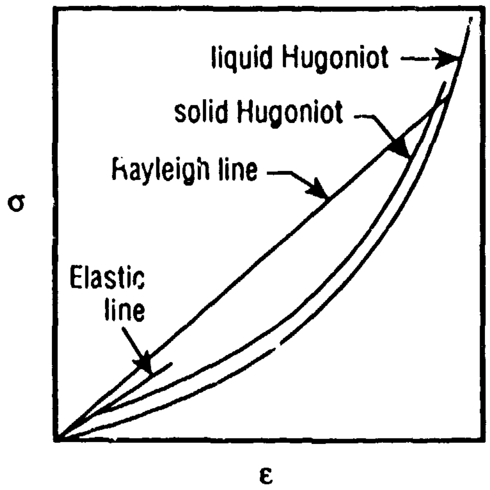

FIGURE 2
For an overdriven shock, the Rayleigh line lies above the elastic line. The solid Hugoniot lies above the liquid Hugoniot on account of the shear strength of the solid.

shown in Figure 2. For a solid, the elastic line is the $\sigma(\varepsilon)$ relation for an adiabatic uniaxial elastic compression; it is given by

$$\sigma = \rho_a c_l^2 \varepsilon , \qquad (5)$$

where c_l is the adiabatic longitudinal sound velocity. By definition, an overdriven shock is one which travels faster than the sound wave, so that $D > c_l$, as shown in Figure 2. Now the question is, how can σ rise above the elastic compression line at small ε, as it must for an overdriven shock in a solid? Certainly plastic flow cannot help, because plastic flow is a response to stress anisotropy, and plastic flow can only act to reduce σ. Therefore, heat must be transported to the small-ε region, since heat will increase σ. Now if heat is available to be transported to the leading edge of the shock, then it must be generated in the later part of the shock, and the only available heat generating mechanism in our solid material is plastic flow. These arguments constitute the physical basis for two theorems on the existence of overdriven steady-wave shocks in solids:[1]

(a) There must be heat transport.

(b) There must be dissipative plastic flow.

Incidentally, for weak (underdriven) shocks in solids, heat transport is not required for the existence of a shock, and indeed, heat transport is quantitatively negligible in the weak shock process.[7]

Both of these theorems extend to a liquid. To see this clearly, we first need to examine the nature of viscoelastic response. Consider a small uniaxial compression ε, resulting from a small normal stress σ, as shown in Figure 1. If σ is applied very slowly, viscous flow proceeds to relieve the shear stress, so that τ remains very small, and the $\sigma(\varepsilon)$ curve is just the isotropic compression curve (pressure-volume curve). If σ is applied more quickly, the $\sigma(\varepsilon)$ curve rises higher, since only a higher τ can drive viscous flow at a higher rate. But when σ is applied quickly enough, there is not time for any viscous flow, so the liquid response switches to elastic, and the $\sigma(\varepsilon)$ curve does not rise any higher. The liquid elastic line is again given by (5), where c_l is the velocity of adiabatic longitudinal sound waves, which propagate in a liquid in the high-frequency (elastic) limit. Now, by definition, an overdriven shock in a liquid is one for which $D > c_l$, so the arguments appropriate to shocks in solids apply, and we find the following theorems on the existence of overdriven steady-wave shocks in liquids:[3]

(a) There must be heat transport.

(b) There must be dissipative viscous flow.

Finally, we note that these theorems both extend to gases, since gases must also display elastic response at sufficiently high strainrates.

The above theorems constitute a significant extension of the classic analysis of Rayleigh in 1910,[8] on shocks in viscous heat-conducting gases. Rayleigh's findings are expressed in two theorems on the existence of steady-wave shocks: (1) For very weak shocks, a solution exists when only thermal conduction is present, and (2) for stronger shocks, a solution exists when only viscous flow is present. For overdriven shocks, of concern here, only Rayleigh's theorem 2 applies, namely that there must be viscous dissipation. Our first theorem, on the necessity of heat transport as well, was not discovered by Rayleigh, since he did not envision the occurrence of elastic response at high strainrates.

Still another interesting property of shocks in liquids was found in our original study:[3] for sufficiently strong shocks, beyond the overdriven threshold, the compression in the leading edge of the shock is purely elastic.

3. SHOCK STRUCTURE IN METALS

For metals, our irreversible thermodynamic theory should be valid for shocks up to several Mbar. With a few approximations, it is possible to estimate the plastic flow data for a metal within the shock process.[2] The shock process involves inexact differentials, such as the differential of work dW, whose integrals are path dependent; hence the shock process has to be integrated along the Rayleigh line, and nowhere else.

Our first approximation is to neglect the shear strength of the shock-compressed solid, i.e. to set $\tau_H = 0$. Then the plastic strain has to be sufficient to release the shear stress to zero at the end of the Rayleigh line, and this gives us an approximate value for ψ_H. Next we introduce the thermal equation of state, giving temperature T and entropy S as functions of U and ρ, and this allows us to calculate T and S along the Hugoniot, so that we know how much heat is generated in the shock. But the heat generated is also the total plastic work, which is the Rayleigh line integral of $2\rho^{-1}\tau d\psi$. Hence, to generate the right amount of heat, we find an estimate of $<\tau>$, the average shear stress on the Rayleigh line. Next we consider

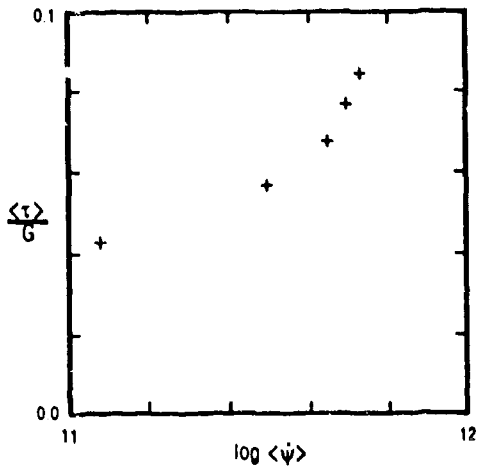

FIGURE 3

Plastic data for Pt within the shock compression, for shocks from 1 to 3 Mbar.

the time scale of the shock. Two different dissipation processes are going on simultaneously within the shock, namely heat conduction and plastic flow. But since the shock is a steady wave, the two dissipation processes have to be going on at the same rate. For a metal, where heat is carried mainly by the conduction electrons, the thermal conductivity κ is only weakly dependent on temperature and density, so a good estimate of κ within the shock is possible. The value of κ then determines the time rate of the whole process, and hence gives an estimate of $<\dot{\psi}>$, the mean plastic strainrate on the Rayleigh line. In this way, we estimated plastic flow data for 2024 Al, and for Pt, for shocks up to melting.[2]

Plastic data for Pt, in the form of $<\tau>/G$ *vs* $\log<\dot{\psi}>$, is shown in Figure 3. G is the shear modulus, evaluated on the Rayleigh line, in the region where $\dot{\psi}$ is maximum. We emphasize that no plasticity modeling has been used here; the results follow entirely from conservation laws, equilibrium thermoelastic data, and an estimate of thermal conductivity. The data should be reliable within a factor of two in $<\tau>/G$, and in $\dot{\psi}$.

Finally, we recall that the risetime of shocks in solid and liquid metals is predicted to decrease to a few picoseconds, as the shock strength increases through the overdriven threshold.[2,3] Since this is a central prediction of the theory, it would be valuable to measure risetimes of shocks in metals around the overdriven threshold.

REFERENCES

1. D. C. Wallace, Phys. Rev. B24 (1981) 5597.
2. D. C. Wallace, Phys. Rev. B24 (1981) 5607.
3. D. C. Wallace, Phys. Rev. A25 (1982) 3290.
4. D. C. Wallace, Thermoelastic-Plastic Flow in Solids (LA-10119, Los Alamos National Laboratory, Los Alamos, 1985).
5. D. C. Wallace, Computer Simulation of Nonequilibrium Processes, in: Shock Waves in Condensed Matter, ed. Y. M Gupta (Plenum, New York, 1986) pp. 37-49.
6. D. C. Wallace, Structure of Shocks in Solids and Liquids (LA-12020, Los Alamos National Laboratory, Los Alamos, 1991).
7. D. C. Wallace, Phys. Rev. B22 (1980) 1487.
8. Lord Rayleigh, Proc. R. Soc. Lond. A84 (1910) 247.