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Theoretical investigation of shock wave stability in metals

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Shock adiabats of metals with different initial volumes and pressures have been calculated with the use of multiphase equation of state. The stability of shock wave has been investigated using the known criteria. We found two types of instabilities occurring in the vicinity and inside two-phase liquid-gas region. They are the specific sound instability arising as a spontaneous sound emission from the shock discontinuity and two-wave configuration. The position of the instability region and its dependence on initial pressure and volume has been analyzed. Discussed are regularities obtained for 30 metals. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2894197]

The shock wave is a unique tool in modern physics of high pressure. It produces uniform distribution of pressure, density, energy, and temperature behind the shock front for short period of time. The thermodynamic properties of shocked matter can be obtained for stationary one-dimensional shock wave with the use of the Hugoniot equations.[1]

The gas dynamic analysis of the Riemann problem allows one to obtain criteria of shock wave stability. It can be done either with the usage of linearized gas dynamic equations[2–8] or on the basis of the general theory of decay and branching of arbitrary discontinuity.[9] The theory predicts two situations. In the first case, the shock wave is unstable[2–5] and decays into other stable "elements" (stable shock waves, isentropic rarefaction or compression waves, tangential discontinuities, see for details,[9] and references therein). The second case corresponds to a possibility of spontaneous emission of sound from the shock front.[6–9]

Such instabilities can occur when the shock adiabat passes through specific regions of the phase diagram, characterized by thermodynamic anomalies. The two-phase liquid-gas region is the most attractive object for investigating the problem of shock wave stability. The basic reasons are that there are parts of the shock Hugoniot with $(\partial V/\partial p)_H>0$ (index H means that the derivative is taken along the shock adiabat) inside the liquid-gas region, the isentropic sound velocity c_S has an anomalously low value near the boundary with the liquid phase and presence of other anomalies in thermodynamic functions. The goal of the work is theoretical investigation of shock wave stability in metals.

The stability of plane shock waves in media with arbitrary equation of state (EOS) has been studied by Dyakov[2] and then in subsequent work.[2–9] It is important to note that the recent analysis done on the basis of the general theory of decay and branching of an arbitrary discontinuity[9] leads to the same formulas obtained previously by use of linearized gas dynamic equations.[2–8] Omitting theoretical calculations, one can write in thermodynamic variables these criteria as

$$(\partial V/\partial p)_H < \frac{V-V_0}{p-p_0}, \tag{1}$$

$$(\partial V/\partial p)_H > [1+2\beta^{-1}(D/c_S)]\frac{V-V_0}{p-p_0}, \tag{2}$$

$$\frac{V-V_0}{p-p_0}\frac{1-\beta^{-2}(D/c_S)^2-\beta^{-1}(D/c_S)^2}{1-\beta^{-2}(D/c_S)^2+\beta^{-1}(D/c_S)^2} \times < (\partial V/\partial p)_H < [1+2\beta^{-1}(D/c_S)]\frac{V-V_0}{p-p_0}. \tag{3}$$

Here, V_0 and p_0 are referred to an initial state, $\beta=V_0/V$ and D is shock velocity.

The case of absolute shock wave instability corresponds to Eqs. (1) and (2). The condition (1) leads to gas dynamic flow with several shock discontinuities, which are separated by rarefaction waves. The condition (2) is much stronger than (1) and, according to Ref. 9, leads to decay of a shock discontinuity into several ones. A criterion of spontaneous sound emission (SSE) is defined by Eq. (3). Note that for fulfillment of this criterion, the presence of region on shock adiabat with $(\partial V/\partial p)_H>0$ is desired.

Equations (1)–(3) have been applied in theoretical investigations with the use of EOS for specific substances. Calculations done with the use of multiphase EOS (Ref. 10) for copper at room pressure $p_0=10^{-4}$ GPa revealed SSE in two-phase liquid-gas region.[11] EOS for water-vapor system made it possible to examine regions of shock wave stability.[12] According to Ref. 12, there are SSE regions and absence of absolute instability in water-vapor system. Analogous results have been obtained for shock adiabats of metals inside liquid-gas region.[13] SSE's region behind strong ionizing shock propagating in inert gases has been reported.[14] An application of quasiclassic Thomas–Fermi theory revealed SSE's region in tungsten at extreme high pressure.[15]

Calculations of shock adiabats for ~30 metals have been done with the use of modified version[16] of multiphase EOS.[10] The initial state has been changed from compressed solid and liquid metal to plasma and gas. These calculations correspond to matter that is in thermodynamic equilibrium.

The anomalous behavior has been found for shock adiabats starting inside two-phase liquid-gas region. Two different types of instabilities have been obtained.

Figure 1 illustrates the evolution of shock adiabats of magnesium started at initial pressure of 10^{-4} GPa. The check of criterion (3) gives parts on these adiabats having the sound instability both inside and outside the liquid-gas re-

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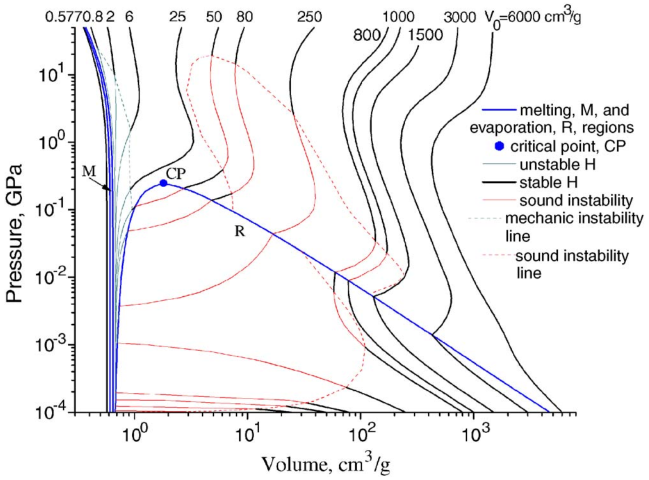

FIG. 1. (Color online) Shock adiabats of Mg at $p_0=10^{-4}$ GPa with different initial volumes V_0.

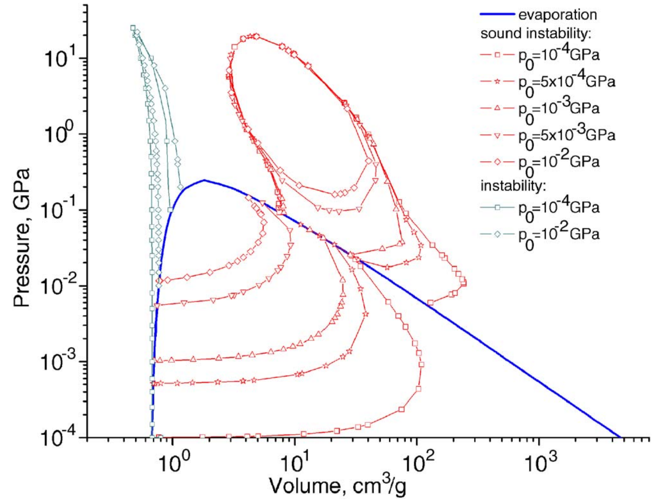

FIG. 2. (Color online) Evolution of instability lines in Mg depending on initial shock pressure p_0.

gion. The corresponding dashed line ("instability" line) forms the boundary for the SSE-instability region so that each shock adiabat crossing this line has unstable parts with respect to SSE. Another situation takes place for shock adiabats with initial volumes $V_0=0.8-250$ cm^3/g. The shock velocity D becomes less than isentropic sound velocity c_S when these shock adiabats cross the phase boundary of evaporation and come to liquid state. In accordance with general principles,[1,17] such a shock transforms into an isentropic compression wave under this condition. The further increasing of pressure restores the condition of shock compression. The corresponding instability (dashed line in Fig. 1) shows the position of this mechanic instability region. Note, that shock adiabats with $V_0=0.8-25$ cm^3/g remain in liquid state while the Hugoniots with $V_0=50-1000$ cm^3/g cross again the evaporation region and exit to gas state. Those adiabats that cross the evaporation region only once have no anomalies in liquid, while the adiabats that cross the evaporation region two times have SSE parts also in gas. It is to be noted that this effect occurs in the gas region again due to specific density dependent behavior of the sound speed in the vicinity of the critical point.

The variation of initial shock pressure p_0 changes the position of instability regions on the phase diagram as it is seen in Fig. 2. The mechanic instability region occurs closer to the critical point at higher initial pressures p_0. The SSE regions inside liquid-gas mixture remain similar geometrically. The geometry of SSE regions outside the liquid-gas mixture is some what different—these domains are separated from the evaporation boundary at pressures $p_0>10^{-3}$ GPa. It is interesting to note, that all these SSE regions are very close at high pressures (see Fig. 2).

As it is seen in Fig. 1, some shock adiabats (for example, with $V_0=0.577$ and $1500-6000$ cm^3/g) have no anomalies. Only adiabats, which initial volume V_0 satisfies to an inequality (the limiting volumes do not coincide with boundaries of liquid-gas region), cross corresponding instability line. These limiting volumes at different initial pressures p_0 are drawn in Fig. 3, so all adiabats, which start under the line, have unstable parts. Let us consider the region under the line as an instability region.

Figure 3 shows that shock adiabats with initial states inside liquid-gas region can have different type of instabilities. The first type is the transformation of shock wave to isentropic compression wave. In the second case, this mechanic instability is supplemented by the sound instability inside and outside the liquid-gas mixture. The third situation corresponds to shock adiabats that cross the evaporating boundary only from the gas side and have only sound instability inside and outside the liquid-gas region.

Note that adiabats crossing the liquid-gas boundary from the liquid side lie below the wave ray (see Fig. 1). Along these parts $(\partial V/\partial p)_H<0$, while entropy is increasing. In this situation, metal is compressed in the centered adiabatic wave S=const which is separated from moving flow by surface, of weak discontinuity.[17]

Like previous analysis done only for shock adiabats inside liquid-gas region,[13] the position of instability lines and instability region is individual for all metals with some similarity in groups of the Periodic Table. The influence of thermal electron contribution in the EOS on the geometry of instability lines and instability region is strong, as it was found previously.[13] Nevertheless, the situation mentioned above for Mg with different types of instabilities of shock adiabats is analogous for all investigated metals. The physical explanation of anomalies of shock compression for the liquid-gas mixture is, namely, the low value of isentropic

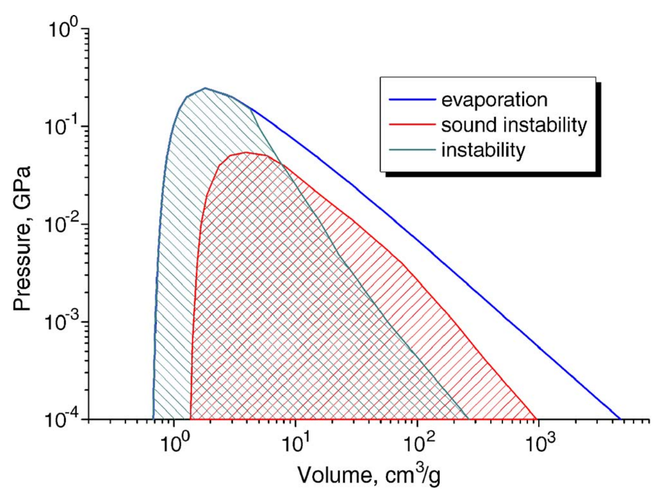

FIG. 3. (Color online) Instability regions in Mg.

sound velocity c_S in this region of the phase diagram.

The stability of shock waves has been studied for different initial pressures and volumes with the use of advanced multiphase EOS for 30 metals. Different types of instabilities have been found for shock adiabats that starts inside liquid-gas region. These mechanic and sound instabilities arise inside and outside liquid-gas region. The dependence of typical regions of these instabilities on initial pressure and volume is reported.

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[1]Y. B. Zeldovich and Y. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena* (Academic, New York, 1966).
[2]S. P. Dyakov, Zh. Eksp. Teor. Fiz. **27**, 288 (1954).
[3]V. M. Kontorovich, Sov. Phys. JETP **6**, 1179 (1957).
[4]S. V. Iordanskii, Zh. Prikl. Matem. Mekh. **21**, 465 (1957) [in Russian].
[5]V. M. Kontorovich, Sov. Phys. JETP **6**, 1180 (1957).
[6]S. P. Dyakov, Sov. Phys. JETP **6**, 729 (1958).
[7]G. R. Fowles, Phys. Fluids **24**, 220 (1981).
[8]L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Pergamon, Oxford, 1987).
[9]N. M. Kuznetsov, Zh. Eksp. Teor. Fiz. **88**, 470 (1985).
[10]A. V. Bushman, G. I. Kanel, A. L. Ni, and V. E. Fortov, *Thermophysics and Dynamics of Intense Pulse Loadings* (Taylor & Francis, London, 1993).
[11]A. V. Bushman, Proceedings of the First SSSR Symposium on Pulsed Pressures, 1976 (unpublished), p. 39.
[12]N. M. Kuznetsov and O. N. Davidova, Teplofiz. Vys. Temp. **26**(3), 567 (1988).
[13]I. V. Lomonosov, V. Fortov, K. V. Khishchenko, and P. R. Levashov, AIP Conf. Proc. **505**, 85 (2000).
[14]M. Mond and I. M. Rutkevich, J. Fluid Mech. **275**, 121 (1994).
[15]T. N. Fortova, A. N. Dremin, and V. E. Fortov, Chisl. Met. Mekh. Splosh. Sredi **4**, 143 (1972) [in Russian].
[16]I. V. Lomonosov, Laser Part. Beams **25**, 567 (2007).
[17]V. E. Fortov, High Temp. **10**, 141 (1972).