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Dynamic Determination of the Compressibility of Metals*

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Equation of state data for Duralumin in the pressure range from 0.1 to 0.3 megabar have been determined dynamically by measuring shock and free surface velocity electrically in a plate of 24 ST Duralumin that has been stressed by a high explosive detonation. A theory is presented which allows comparison with data obtained by other experimenters, and which yields the relationship between pressure and compression either at constant entropy or constant temperature. The empirical form chosen for the equation of state ($p=\alpha\mu+\beta\mu^2$) expresses the pressure as a quadratic function of the compression. Experimental techniques are described in detail. Five points are given for the equation of state of Duralumin in the pressure range from approximately 0.15 megabar to 0.33 megabars. Some data are also presented for cadmium and steel.

INTRODUCTION

EARLY in 1945 experimental work was initiated at the Los Alamos Scientific Laboratory for the study of physical properties of materials in the pressure range from 0.1 to 0.3 megabar (10^{12} dynes/cm^2). One-tenth of a megabar had been obtained statically at the Geophysical Laboratory of the Carnegie Institution, but determinations of the equation of state at this pressure become impractical partly because of the elaborate and cumbersome apparatus required and partly because static measurements are subject to uncertainties resulting from creep distortions. An alternative technique, and one particularly suited to the data here desired, is to make the measurements dynamically, thereby eliminating the need for elaborate high pressure equipment with its inherent creep uncertainties.

It is, of course, well known that extreme, though temporary, pressures can be developed by high explosives. With suitably designed apparatus, detonation of a high explosive may be made to produce in the material being investigated a plane shock wave approximately flat-topped in the sense that the pressure in the compressed material is virtually independent of position. The conditions for the existence and stability of such shock waves are discussed in a variety of textbooks.[1]

The theory of propagation of such waves implies that simultaneous determinations of the propagation velocity of the wave and of the mass velocity of the compressed material can be used to infer the equation of state. In addition it is possible under certain conditions to determine shock pressures by means of piezoelectric crystals though this last technique has proved rather difficult to exploit.

THEORY

Detonation of high explosive in contact with a metallic specimen produces pressures in the metal under what are usually termed "Rankine-Hugoniot Shock" conditions. Such conditions will be denoted by appending the subscript D to the symbols appearing in Table I. The mechanical considerations of conservation of mass and conservation of momentum, respectively, lead to the equations:

$$\eta-1=\mu=u/(D-u) \tag{1}$$

$$p_D=\rho_0 Du. \tag{2}$$

The pressures and compressions appearing in Tables II and III were computed by means of Eq. (1) and (2). For many purposes, for example in comparing our data with other data, it is necessary to know the relationship between pressure and compression either at constant entropy or at constant temperature. Such conditions will be specified by the subscripts s and T, respectively. In order to compute the difference between p_D and p_s or

TABLE I. Definitions of symbols and list of units to be used in computation.

Symbol	Definition	Units
p	pressure	megabar $=10^{12}$ dynes/cm^2
v	specific volume	cm^3/g
ρ	density at pressure p	g/cm^3
ρ_0	initial density	g/cm^3
$\eta-1=\mu$	compression -1 $=(\rho-\rho_0)/\rho_0$[a]	....
e	specific internal energy	cm^3-megabar/g $=10^{12}$ ergs/g
T	absolute temperature	electron volt $=\kappa T=11{,}605°$C
s	specific entropy	cm^3-megabar/g-ev
C_v	specific heat at constant volume $=(\partial e/\partial T)_v$	cm^3-megabar/g-ev
D	shock wave velocity	cm/μsec $=$ cm/10^{-6} sec
u	particle or mass velocity	cm/μsec $=$ cm/10^{-6} sec
σ	excess of free surface velocity over mass velocity	cm/μsec $=$ cm/10^{-6} sec
c	velocity of sound $=(\partial p/\partial\rho)_s^{\frac{1}{2}}$	cm/μsec $=$ cm/10^{-6} sec
α_s	isentropic bulk modulus at $p=0$	megabar
β_s	second-order coefficient in empirical isentropic equation of state; see Eq. (17)	megabar

[a] Compression is alternatively defined as $(v_0-v)/v_0=(\eta-1)/\eta$, where v_0 is the normal specific volume.

$\mu = \eta - 1 = \frac{V_0}{\Delta V}$

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[1] e.g., Courant-Friedrichs, *Supersonic Flow and Shock Waves* (Interscience Publishers, Inc., New York, 1948), p. 121 *et seq.*