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An Equation of State for Shocked Copper Foam

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by

Charles L. Mader

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ABSTRACT

The experimentally observed behavior of systems of high-explosive, low-density (ρ_0 = 6.62 g/cm^3) copper foam in contact with uranium, copper, tin, aluminum, magnesium, Plexiglas, wax, methyl pentene, cherry wood, and air can be numerically reproduced.

I. Introduction

The objective of this study was to reproduce numerically the experimentally observed behavior of Composition B, imparting a shock to low-density (ρ_0 = 6.62 g/cm^3) copper foam in contact with materials that would send a shock or a rarefaction back into the copper foam. This study is similar to one performed on polyurethane foam described in Ref. 1.

Broade[2] reported low-pressure Hugoniot data for copper foam, and Herrmann[3] proposed an equation of state for the low-pressure, uncompacted region. McQueen[4] and Broade,[2] among others, reported high-pressure Hugoniot data for porous copper. McQueen[4] showed that above 50 kbar the experimentally measured Hugoniots of foamed metals can be approximated by using the Hugoniot equation of state of the metal at crystal density and the Grüneisen equation of state to correct for the higher energy of the metal at the same shocked volume.

We have found that such a procedure can be used to reproduce the experimentally observed shock parameters of shocked (375 kbar) copper foam that has been double shocked (up to 650 kbar) or rarefied (down to 100 kbar). For shocks that result in densities between foam density and slightly above crystal density, a separate experimentally determined equation of state is required. Below crystal density of the metal, the release isentrope is calculated by using the zero-pressure curve as the standard curve and the Grüneisen equation of state. This is the least satisfactory feature of the model because major adjustments of the equation-of-state parameters for copper are required to reproduce the experimentally observed data.

II. The Experimental Data

Carter[5] measured the shock velocities by using the flash-gap technique of approximately 0.5-cm-thick plates of uranium, copper, tin, aluminum, magnesium, Plexiglas, wax, methyl pentene, and cherry wood in contact with 0.762 cm of 6.62 g/cm^3 sintered copper foam that had been shocked to about 375 kbar by an explosive system consisting of a P-80 plane-wave lens and 20.32 cm of Composition B-3. Carter's experimental results are shown in Table I.

Broade[2] has reported the low-pressure Hugoniot data for 6.052 and 7.406 g/cm^3 foamed copper. Using Broade's shock-particle velocity data, we interpolated to obtain a linear shock velocity, particle velocity curve for 6.62 g/cm^3 copper foam of $U_s = 0.05 + 1.60\, U_p$. This was used up to about 12 kbar where compaction should be complete. This approach was chosen for coding convenience. Herrmann's[3] method should be as good, if not better, for reproducing the experimental data.

III. The Calculations

The SIN one-dimensional hydrodynamic code[6] was used to calculate the detonation of the Composition B-3 and the resulting interaction with layers of foam and metals or plastic. The equation of state used in SIN is the HOM[6] equation of state.

The Nomenclature

C,S	coefficients to a linear fit of U_s and U_p
F,G,H,I,J	coefficients to log fit of Hugoniot temperature as a function of volume

TABLE I

EXPERIMENTAL AND CALCULATED RESULTS

			Calculated				
Plate	ρ_0 g/cc	Experimental Shock Velocity (cm/μsec)	Shock Velocity (cm/μsec)	Particle Velocity (cm/μsec)	Pressure (Mbar)	Foam Temperature (°K)	Linear Coefficient of Expansion (α)
Uranium	18.33	0.400	0.390	0.091	0.650	3130	
Copper	8.903	0.552	0.554	0.106	0.521	2920	
Tin	7.28	0.454	0.450	0.126	0.413	2700	
Cu Foam	6.62	0.410	0.410	0.138	0.375	2600	
Dural	2.785	0.733	0.735	0.148	0.303	2440	
Magnesium	1.77	0.666	0.661	0.166	0.195	2200	
Plexiglas	1.18	0.547	0.538	0.187	0.119	2020	
Wax	0.918	0.596	0.590	0.192	0.104	1950	1.76×10^{-5}
			0.594	0.194	0.106		6.0×10^{-5}
Methyl Pentene	0.83	0.527	0.523	0.198	0.086	1940	1.76×10^{-5}
			0.530	0.202	0.089		6.0×10^{-5}
Cherry Wood	0.60	0.370	0.344	0.210	0.043	1930	1.76×10^{-5}
			0.355	0.218	0.046		6.0×10^{-5}
Free Surface		0.245	0.225			1900	1.76×10^{-5}
			0.245			1700	6.0×10^{-5}

C_V	heat capacity (cal/g/deg)
I	total internal energy (Mbar-cm^3/g)
P	pressure (Mbar)
T	temperature (°K)
U_p	particle velocity
U_s	shock velocity
V	total volume (cm^3/g)
Vo	initial volume (cm^3/g)
α	linear coefficient of thermal expansion

Subscripts

H	Hugoniot
o	initial condition
f	foam

For volumes less than crystal V_0 of the metal or switch volume, whichever is smaller, the experimental Hugoniot is expressed as a linear fit of the shock and particle velocities. The Hugoniot temperatures are computed by the Walsh and Christian technique described in Ref. 6.

$$U_s = C + SU_p \quad ,$$

$$P_H = \frac{C^2 (V_o - V)}{[V_o - S(V_o - V)]^2} \quad ,$$

$$\ln T_H = F + G \ln V + H (\ln V)^2 + I(\ln V)^3 + J(\ln V)^4 \; ,$$

$$I_H = ½\, P_H(V_o - V) \quad ,$$

$$P = \frac{\gamma}{V}(I - I_H) + P_H \text{ , where } \gamma = V(\frac{\partial P}{\partial I})_V \sim 2S - 1 \; ,$$

and

$$T = T_H + \frac{(I - I_H)(23{,}890)}{C_V} \quad .$$

For volumes greater than crystal V_o, we use the Grüneisen equation of state and the P = 0 line as the standard curve if the foamed metal has previously been compressed to less than crystal V_o. Because on the P = 0 line,

$$I = \frac{C_V}{23890} (T - T_o) \quad ,$$

$$\frac{V}{V_o} - 1 = 3a(T - T_o) \quad ,$$

$$I = \frac{C_V}{(3)(23890)\,a}\left(\frac{V}{V_o} - 1\right) \quad ,$$

then

$$P = \left[I - \frac{C_V}{(3)(23890)(a)}\left(\frac{V}{V_o} - 1\right)\right]\frac{\gamma}{V} \quad ,$$

and

$$T = \frac{(I)(23890)}{C_V} + T_o \quad .$$

The equation of state used between foam V_o^f and near-crystal V_o, or switch volume, was a linear fit of the shock and particle velocities identical to that previously described for volumes less than crystal V_o with the foam C, S, and V_o^f. The switch volume was chosen as the volume where the Hugoniot pressure of the two equations of state was identical. After a cell had been compressed to greater than switch volume, the SIN spall flag was used as an indicator. This also resulted in the cell spalling if it developed any tension at later times.

The equations of state used in the SIN calculations are given in Table II except for the Becker-Kistiakowsky-Wilson parameters for Composition B-3 given in Ref. 7.

The resulting copper and foamed-copper Hugoniots are shown in Figs. 1 and 2 with the reflected shock and isentropes through the 375-kbar, foamed-copper Hugoniot point.

The experimental and calculated results are shown in Table I. The equation of state appears to reproduce the observed behavior of the foamed copper remarkably well,

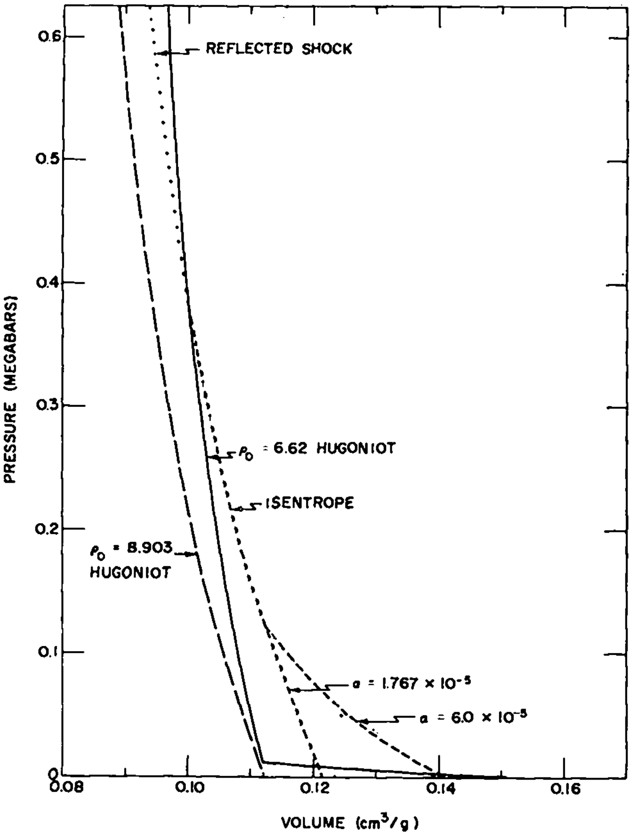

Fig. 1.
The pressure-volume Hugoniot of compressed copper and foamed copper and the reflected shock and isentrope through the 375-kbar, foamed-copper Hugoniot point.

TABLE II

EQUATION-OF-STATE PARAMETERS

	U	Cu[a]	Sn	Al	Mg	Plexiglas	Wax	Foam Cu	Methyl Pentene	Cherry Wood
ρ_0	+18.33	+8.903	+7.28	+2.785	+1.77	+ 1.18	+0.918	+6.62	+0.83	+0.60
C	+ 0.254	+0.3958	+0.264	+0.535	+0.470	+ 0.2432	+0.2908	+0.05	+0.215	+0.05
S	+ 1.50	+1.497	+1.476	+1.35	+1.148	+ 1.5785	+1.56	+1.60	+1.56	+1.40
γ	+ 2.0	+2.0		+1.70	+1.30	+ 1.0	+2.12	+2.0	+2.12	+1.80
$a(\times 10^5)$	+ 1.166	+1.767	+2.0	+2.4	+2.56	+10.0	+1.0	+6.0		
C_V	+ 0.0276	+0.093	+0.054	+0.22	+0.25	+ 0.35	+0.50	+0.093		
Switch V								+0.112		

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[a] For copper, the coefficients to the temperature fit are F = −3.19834199166 + 03, G = −5.57439532793 + 03, H = −3.62488400413 + 03, I = −1.04339679508 + 03, J = −1.12067263866 + 02.

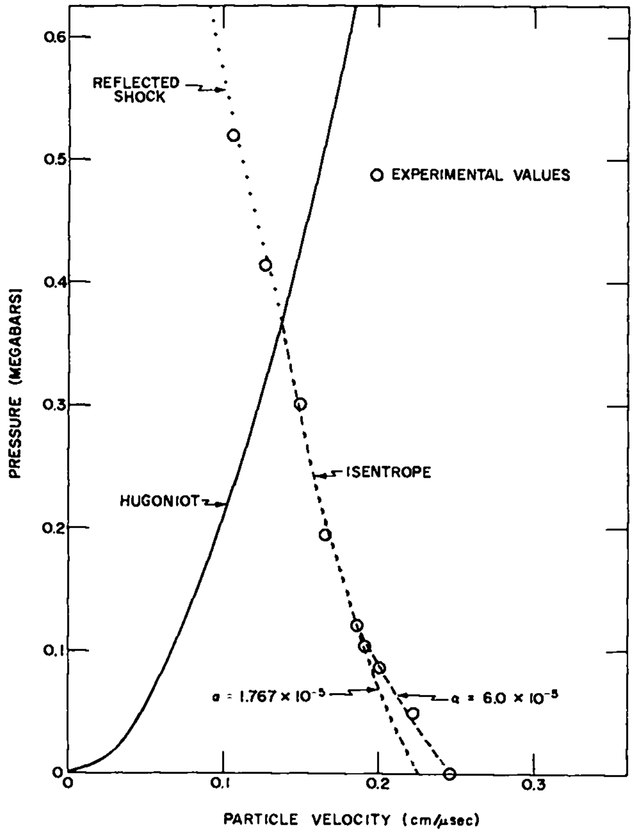

Fig. 2.
The pressure-particle velocity Hugoniot and reflected shock and isentrope through the 375-kbar, foamed-copper Hugoniot point. The experimental values are shown for Cu, Sn, Al, Mg, Plexiglas, wax, methyl pentene, cherry wood, and the free surface.

at least until the hot foamed copper is rarefied to below 100 kbar. Below crystal density, the release isentrope calculated by using the usual low-temperature parameters does not agree with the experimental isentrope values. A linear coefficient of expansion of approximately 6 x 10^{-5} instead of the low-temperature value of 1.767 x 10^{-5} is required to obtain a calculated release isentrope that agrees with the experimental data.

The residual temperature of the foamed copper is so high (1900°K) that it is above the melting point of copper (1356°K). The experimental values of the low-pressure copper coefficient of thermal expansion at 1300°K is approximately 3.0 x 10^{-5}.[8] The heat capacity increases from 0.093 to 0.11 after melting.[8] Although one can account for some decrease in (C_V/α), it is insufficient to account for the amount required to reproduce the low-pressure experimental data.

The high linear coefficiënt of expansion results in a sharp change of slope of the isentrope, which is probably unrealistic. More and better experimental data would be required to determine how the slope of the isentrope is actually changing.

IV. Conclusions

The behavior of Composition B shocking low-density (6.62 g/cm^3) copper foam in contact with uranium, copper, tin, aluminum, magnesium, Plexiglas, methyl pentene, wax, and cherry wood plates that send a shock or rarefaction back into the copper foam has been experimentally determined. The experimentally observed behavior may be reproduced by using the SIN code if the equation of state of the foam is approximated above crystal density by the Hugoniot equation of state of the metal at crystal density and if the Grüneisen equation of state corrects for the higher energy of the foamed metal. For shocks of less than 12 kbar and densities between foam density and slightly above crystal density, a separate experimentally determined equation of state is used. Below crystal density of the metal, the release isentrope is calculated by using the zero pressure curve as the standard curve and the Grüneisen equation of state. A coefficient of linear expansion several times larger than the low-temperature coefficient was necessary to reproduce the experimental data below 100 kbar. The details of the release isentrope equation of state below 100 kbar is therefore in considerable doubt, and additional experimental and theoretical studies in this region would be rewarding.

V. Acknowledgment

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