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Shock wave equation of state of powder material

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A model is proposed to predict the following quantities for powder materials compacted by shock waves: the pressure, the specific volume, the internal energy behind the shock wave, and the shock-wave velocity $U_s$. They are calculated as a function of flyer plate velocity $u_p$ and initial powder specific volume $V_0$. The model is tested on Cu, Al2024, and Fe. Calculated $U_s$ vs $u_p$ curves agree well with experiments provided $V_0$ is smaller than about two times the solid specific volume. The model can be used to predict shock-wave state points of powder or solid material with a lower or higher initial temperature than room temperature.

I. INTRODUCTION

Since the 1960s various approaches have been followed in describing the shock-wave equation of state (EOS) of powder materials. Roughly speaking modeling was done in two different ways: i.e., semiempirically, using quasi-static powder compaction models$^1$-5 and purely theoretically.$^6$-11 Except for Ref. 11 these models adopt the Mie-Griineisen EOS, which relates the change in internal energy to the change in pressure at constant specific volume: $dE = V dP / \Gamma(V)$. In many materials the Mie-Griineisen constant $\Gamma(V_0)$ ranges between 1.6 and 2.6.

These models, however, have some drawbacks because the internal energy and the pressure are divided into separate contributions of cold isothermal compressive and thermal components: $E = E_C + E_T$ and $P = P_C + P_T$, respectively. It follows that the pressure behind the shock wave is given by

$$P = \frac{2P_C V - 2\Gamma(V) E_C}{2V + \Gamma(V) V - \Gamma(V) V_0^2}.$$  \hspace{1cm} (1)

$P_C$ is always represented by the second-order isothermal Birch-Murnaghan EOS. This relationship is not very accurate and rather questionable.$^{12,13}$ Further, for the cold isotherm $E_C$ is supposed to be $E_C = \int P_C dV$. This is certainly not the case as it only holds for the adiabat and a large error is introduced. In addition the derivative of the isothermal bulk modulus $K_0$ with respect to pressure is needed as an input parameter for the Birch-Murnaghan relation. This value is difficult to determine experimentally.

Finally, it is clear that when $V_0 > V_0^2[1 + 2/\Gamma(V_0)]$, the increasing linear denominator crosses the specific volume axis at the right of $V_0$ at $V = \{\Gamma(V)/[2 + \Gamma(V)]\} V_0$. Now $P$ is calculated between $V_0$ and $V = \{\Gamma(V)/[2 + \Gamma(V)]\} V_0$ using the negative part of $P_C$. Since the Birch-Murnaghan EOS is only estimating $P_C$ in the case of compression, Eq. (1) fails.

In this article another theoretical approach is reported that takes Oh and Persson's work$^{11}$ as a starting point while using the Mie-Griineisen EOS instead.

II. BASIC CONCEPTS

A. Shock-wave conservation EOS for solid and powder material

Suppose a rigid planar flyer plate of infinite mass propagates at a constant velocity $u_p$. When it impacts onto solid or powder materials these will be compressed and a shock wave with velocity $U_s$ will propagate through the material. The situation is schematically displayed in Fig. 1. The pressure, specific volume, internal energy, and temperature ahead and behind the shock front are represented by $P_0$, $V_0$, $E_0$, and $T_0$, and $P$, $V$, $E$, and $T$, respectively for solid material and $P_0$, $V_0$, $E_0$, and $T_0$ and $P'$, $V'$, $E'$, and $T'$, respectively, for powder material.

Figure 1(b) shows what happens to a powder material during shock-wave compaction. The powder is represented by separate infinite thin material plates. When the first plate collapses on the shock front, it behaves exactly like a solid material. Since there is some space left between the first and the second material plate, the first plate, after being compacted, starts to expand. Its compressive energy is transformed into internal kinetic energy. Then, more plates collide leaving the first plate oscillating between the flyer plate and the second plate. This goes on until all its internal kinetic energy is transformed to random thermal energy. Eventually the first flyer plate is "locked" in its final specific volume. For material with a higher $V_0$, behind the shock wave, more compressive energy is transformed to thermal energy. At first instance this transformation step does not take place in solid material. During pressure release the (remaining) compressive energy part is transformed and/or transferred to the surrounding material.

In order to derive EOS for shock compacting solid and powder material, the following four assumptions have to be made.

(a) It is assumed that compaction of a powder at zero pressure quasi-statically from $V_0$ to the solid specific volume $V_s$ does not cost any energy, so that $E_s = E_0$.

(b) Behind the shock wave there are no voids present, i.e., the material is completely compacted.

(c) The increase in internal energy is equally distribu-
FIG. 1. (a) A rigid flyer plate impacts onto a solid or powder material. Area I is the flyerplate, area II is the compacted powder or solid material, area III is the uncompacted powder or solid material at rest. The flyerplate velocity is \(u_p\) or \(u_i\) (up = \(u_i\)). The shock-wave velocity is \(U_s\) or \(V_s\). (b) The powder is represented by separate solid plates collapsing sequentially on the shock-wave front.

(4)

B. Conservation of mass

The condition that the mass flux in and out the shock front must be equal is expressed by

\[ VU_s = V_0(U_s - u_p), \]

where for powder material

\[ V'U'_s = V_0(U'_s - u'_p). \]

Taking \(u_p\) equal to \(u'_p\),

\[ U_s(V_0 - V)/V_0 = U'_s(V_0 - V')/V_0. \]

C. Conservation of momentum

The change of momentum of material impacted by a flyer plate with surface \(A\) in a time lapse \(\delta t\) is given by \(\delta P = mv\), where \(m = AU_0\delta t/V_0\) and \(v = u_p\). Pressure is the change of momentum per unit area per unit time, so the momentum has to be divided by the impact area \(A\) and the impact time \(\delta t\) in order to obtain the (mean) pressure difference over the shock front. Taking \(P_0 = 0\),

\[ P = \delta P = \frac{U'_s u'_p}{V_0}, \]

where for powder material

\[ P = \frac{U'_s u'_p}{V_0}. \]

Taking \(u_p\) equal to \(u'_p\) leads to \(PV_0/U_s = PV_0/U'_s\).

D. Conservation of energy

Suppose the compacted material is at rest and the uncompacted material collides with a velocity \(u_p\) onto the shock front. Then the change of compressive and thermal energy of material impacting onto an area \(A\) in a time lapse \(\delta t\) is given by \(dE = mv^2/2\), where \(m = AU_0\delta t/V_0\) and \(v = u_p\). The change of internal energy \(\delta E\) is defined as the change of internal energy per unit mass, i.e.,

\[ \delta E = E - E_0 = \frac{1}{2}u_p^2, \]

and for powder material

\[ E' - E_{00} = \frac{1}{2}u_p'^2. \]

By taking \(u_p\) equal to \(u'_p\) and since \(E_{00} = E_0\) [assumption (a)], the increase in internal energy is exactly the same for solid and powder material, i.e., \(E - E_0 = E' - E_{00}\), and only depends on \(u_p\).

Recall that the work done by the flyer plate per kg of compressed material initially at rest is \(u_p^2\) in which \(u_p^2\) per kg is converted in increasing the internal energy of the compressed material and \(u'_p^2\) per kg is converted in increasing the kinetic energy. By combining Eqs. (2) and (4) and Eqs. (3) and (5) the powder \(P', V'\) state points can be related to the solid \(P, V\) state points,

\[ E' - E_{00} = \frac{1}{2}P'(V_0 - V') = \frac{1}{2}P(V_0 - V). \]

E. Solid system

The three solid conservation relations Eqs. (2), (4), and (6) contain four known variables, \(E_0, P_0, V_0,\) and \(u_p\), and four unknown variables, \(E, P, V,\) and \(U_s\). One more relation between any two variables is necessary.

For solid and powder materials \(U_s\) can be measured at different values of \(u_p\). From these data it is known that the relationship between \(U_s\) and \(u_p\) for solid material is nearly linear, i.e., \(U_s = C + Su_p\), where \(C\) is approximately the zero pressure sound velocity and \(S\) is a constant. Combining Eqs. (2) and (4) with the linear relationship of \(U_s\) with \(u_p\) leads to an expression for the pressure behind the shock wave,

\[ P = \frac{C}{[V_0 - S(V_0 - V)]^2}. \]

Equation (9) describes the solid Hugoniot which is the locus of the final shock state, but not the thermodynamic path followed by the material. The Hugoniot is an adiabat, neither an isotherm nor an isentrope. The actual thermodynamic path followed is a straight line from the initial to the final state, called the Rayleigh line.

III. CALCULATIONS

When a flyer plate impacts onto a sample, either solid or powder material, the internal energy increase equals the
FIG. 2. (a) Copper Hugoniot and equienergy curves (b) $E-E_0=0.25$ MJ; (c) 0.50 MJ; (d) 0.75 MJ; (e) 1.00 MJ; (f) 1.25 MJ. The internal kinetic energy is zero. At fixed flyer-plate velocity, behind the shock wave, the internal energy of both the compacted solid and the powder material are the same. Therefore, the final $P$, $V$ point must lie somewhere on the equienergy curve (0→2); only explosive compaction of solid material; (0→1) explosive compaction (0→2) and heating at constant volume (2→1); (0→4); only heating at zero pressure; (0→3); heating at zero pressure (0→4) and heating at constant volume (4→3).

The total amount of internal energy, deposited by the flyer plate to the powder (00→1) (Fig. 2) is given by Eq. (16).

At given $V_0$ and $V_1$, $P_1$ can be calculated using Eq. (16). $u_p$ and $E_1-E_0$ are calculated using Eq. (10) after which $U_s$ can be calculated either with Eq. (3) or Eq. (5).

B. $U_s$ vs $u_p$ calculation for powder materials: $V_3>V_0$

The total amount of internal energy, deposited by the flyer plate in the powder (00→3) (Fig. 2) is given by Eq. (8),

$$E_3-E_0=\frac{1}{2}P_3(V_0-V_3) u_p^2.$$  (17)

This amount of internal energy can quasistatically be stored in the system by heating solid material at zero pressure from $V_0$ to $V_3$ (0→4) and then heating at constant volume $V_4$ from $P_3$ to $P_4$ (4→3).
So, at first the material is thermally expanded to a volume $V_4$, after which $T_4$ and $E_4 - E_0$ are calculated from the temperature-dependent thermal-expansion coefficient $\alpha(T)$ and the specific heat at constant pressure $C_p(T)$. The volume and the temperature are related according to

$$\int_{V_0}^{V_4} \frac{1}{V} dV = \int_{T_0}^{T_4} 3\alpha(T) dT.$$  \hfill (18)

For many solids, over a wide temperature range, i.e., $T_0 < T_4 < \pm 1300$ K, $\alpha(T)$ can be estimated accurately by $\alpha(T) = \alpha(T_0) + \beta(T)(T - T_0)$. Substituting $\alpha(T)$ in Eq. (18) relates $V_4$ to $T_4$,

$$\ln \frac{V_4}{V_0} = 3\alpha(T_0)(T_4 - T_0) + \frac{3}{2} \beta(T)(T_4 - T_0)^2.$$  \hfill (19)

The energy needed to expand to $V_4$ is given by

$$E_4 - E_0 = \int_{T_0}^{T_4} C_p(T) dT.$$  \hfill (20)

For many solids, over a wide temperature range, i.e., $T_0 < T_4 < \pm 1300$ K, $C_p(T)$ can be estimated accurately by $C_p(T) = C_{p_0}(T) + \gamma(T)(T - T_0)$. Substituting $C_p(T)$ in Eq. (20) leads to

$$E_4 - E_0 = C_{p_0}(T_0)(T_4 - T_0) + \frac{1}{2} \gamma(T)(T_4 - T_0)^2,$$  \hfill (21)

where $T_4$ can be calculated using Eq. (21). Note that $\alpha(T)$ and $C_p(T)$ are calculated from experimental values for $V_4(T)$ and $E_4(T) - E_0$, respectively. Whenever available it is better to use direct experimental values for $V_4$ as a function of $E_4 - E_0$.

The internal energy increase along the isochore from $P_4$ to $P_3$ is given by (4 - 3)

$$E_3 - E_4 = \frac{(P_3 - P_4)V_3}{\Gamma(V_3)},$$  \hfill (22)

where $\Gamma(V_3)$ is given by Eq. (15). Finally, the pressure in the fully shock-compacted powder material is given by

$$P_3 = \frac{2\Gamma(V_3)}{\Gamma(V_3)(V_{00} - V_3) - 2V_3} \int_{T_0}^{T_4} C_p(T) dT.$$  \hfill (23)

Since $V_{00}$ and $V_3$ are chosen, $T_4$ is calculated with Eq. (19), $P_3$ is calculated with Eq. (23), $u_p$ and $E_3 - E_0$ are calculated with Eq. (17), after which $U_r$ is calculated with Eq. (3) or Eq. (5).

The model can calculate $U_r$ vs $u_p$ values for powder and solid material as well at higher initial temperature than $T_0$. Further, in principle it is possible to calculate the solid Hugoniot, i.e., the constant $S$. Temperature calculations are presented in Ref. 8.22

IV. VALIDATION OF THE MODEL

In the compaction by shock waves of powder material there are six principal parameters having a main effect on the final compacted material. These are the particle or flyer plate velocity, which is mainly determined by the detonation velocity of the used explosive; next, the initial specific volume of the powder to be compacted, the particle grain size, the initial temperature, and the duration of the shock pressure, which is mainly determined by the size of the experiment. Finally, the compacted powder material, still at pressure, contains adiabatic compressive energy and thermal energy. The adiabatic part has to be transmitted to the surrounding material (flyer plate, canning material), otherwise extensive cracking will occur.

$U_r$ vs $u_p$ relations are calculated for Cu, Al2024, and Fe powder materials and compared with experimental data14 (Figs. 3 - 5). Other material data are from Refs. 14, 16, 19, 20, and 21. It can be concluded that for $V_{00} < \pm 1.8 V_0$ powder $U_r - u_p$ calculations fit well with experiment. The amount of energy $E_G$ needed to compact a homogeneous powder quasi-statically to full density mainly depends on the particle shape and is fixed. For powder material, the larger the $u_p$, the larger the ratio $E - E_0/E_G$ and in that case the better the model. So, the violation of assumption (a) in Sec. II depends on the flyer-plate veloc-

FIG. 3. $U_r$ vs $u_p$ relationship for Cu (solid line: calculated; dashed line: experiment).

FIG. 4. $U_r$ vs $u_p$ relationship for Al2024 (solid line: calculated; dashed line: experiment).
heavy canning material should be applied since the canning material will absorb the adiabatic compressive energy. The model indicates that: although at a given \( u_p \) for less dense powder more compressive energy is transformed to thermal energy the temperature behind the shock wave is roughly the same; at relatively high-flyer-plate velocities, e.g., \( u_p > \pm 3000 \text{ m/s} \), calculated \( U_s \) vs \( u_p \) lines may even cross.

For Cu, Al2024, and Fe, \( V_{\infty} < \pm 1.8 V_n \) the model predicts very well the \( U_s \) vs \( u_p \) relationship. At larger specific volume and \( u_p > \pm 2000 \text{ m/s} \) the calculated \( U_s \) values become too large. With the model it is easy to calculate \( U_s \) vs \( u_p \) relations of powders at temperatures other than room temperature.

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