Shock wave velocity and shock pressure for low density powders: A novel approach

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A novel approach is presented to predict the shock wave velocity as well as the shock wave pressure in powder materials. It is shown that the influence of the specific volume behind the shock wave on shock wave velocity and shock pressure decreases with decreasing initial powder density. The new model is compared with experimental data of various materials: Fc, Cu, Al, C, UO_2, Ce_2O_3, SiO_2 (quartz), NaCl, and polystyrene. It is concluded that the model holds in particular for initial powder densities less than 50% and for flyer plate velocities up to 5 km/s.

Since the 1950's a large amount of shock wave powder compaction experiments have been carried out in order to obtain highly dense crack-free materials with rather unique material properties. The principal problem still to be solved is finding a route to avoid macrocracking during pressure release. Macrocracking can best be avoided when the following three basic rules are obeyed.[1,2] (i) The shock wave pressure should be low. This can be done by lowering the initial powder density. (ii) The pressure release rate should be as small as possible by which tensile stresses in the compacted material at the end of pressure release remain low. (iii) The initial temperature of the powder should be high. In that case the powder ductility increases and the material can still be compacted at low shock wave pressures. These basic rules can be obeyed by shooting a flyer plate on an infinite amount of low density, high temperature powder material by which the flyer-plate velocity and consequently the shock pressure decrease relatively slowly. However, this is in contrast with conventional experimental setups where a small amount of highly dense powder material, originally held at room temperature, is compacted. Recently, we developed a thermodynamic model[1,2] to describe the compaction of powder materials by shock waves and to calculate the shock wave velocity as well as the shock pressure. This model is mainly applicable for powder material at a density (D) greater than 40% whereas in this letter a novel model is presented to be valid for initial densities less than about 50%.

For solid material the shock wave equation of state for mass, momentum, and internal energy are described by[1,3]

$$U_s = \frac{V_{00} u_p}{V_{00} - V},\tag{1}$$

$$P = \frac{U_s u_p}{V_{00}} = \frac{u_p^2}{V_{00} - V},\tag{2}$$

$$E - E_{00} = \frac{1}{2} u_p^2,\tag{3}$$

where u_p, U_s, V, V_{00}, P, and $E - E_{00}$ refer to the particle velocity, shock wave velocity, specific volume behind the shock wave, initial powder specific volume, shock wave pressure, and internal energy increase, respectively.

Suppose a powder shock model is developed, predicting the specific volume to be $V + \delta V$ instead of V, where δV can be either positive or negative. Then the predicted U_s^p and P^p are altered accordingly by replacing V in Eqs. (1) and (2) by $V + \delta V$.

It is obvious that δV has an equal effect as far as the deviation is concerned on U_s^p and P^p. For each value of V and V_{00} a fixed error (err) is allowed in predicting U_s^p and P^p. Then the maximum value of δV, for each (V, V_{00}), is calculated from

$$\text{err} = 1 - \frac{U_s^p}{U_s} = 1 - \frac{P^p}{P}.\tag{4}$$

By substitution of Eq. (1) and the corresponding equation of U_s^p into Eq. (4), δV normalized to V_0, can be written as

$$\frac{\delta V}{V_0} = \frac{\text{err}}{1 - \text{err}}\left(\frac{V}{V_0} - \frac{V_{00}}{V_0}\right),\tag{5}$$

where V_0/V_{00} represents the initial powder density D.

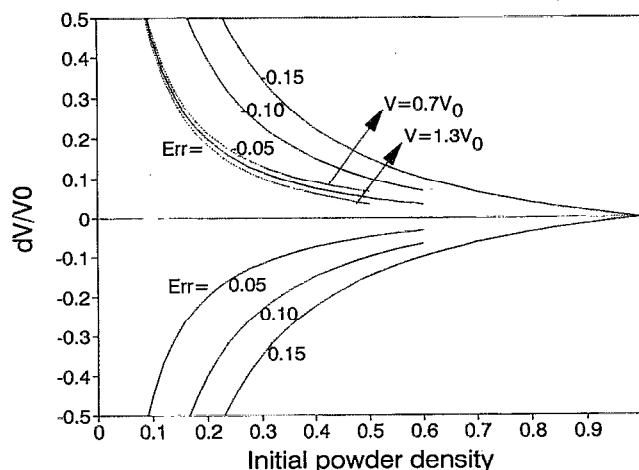
FIG. 1. $\delta V/V_0$ vs initial powder density. Between the border lines the errors in U_s^p and P^p are below 5%, 10%, and 15%, respectively. V has been chosen to be $V = V_0$. When V differs from V_0, e.g., $V = 0.7V_0$ or $V = 1.3V_{0.3}$, $\delta V/V_0$ does not change much.

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In Fig. 1 the $\delta V/V_0$ vs D relationship is displayed for various values of err. In addition, the effect of the specific volume behind the shock wave is depicted. The accuracy in the determination of U_s^p and P^p is chosen to be 5% so that err equals err$=\pm0.05$. err$=\pm0.10$ and err$=\pm0.15$ curves are drawn as well. When for instance $V=0.7V_0$ or $V=1.3V_0$, $\delta V/V_0$ does not change much.

Now, what can be learned from Fig. 1? Suppose a model predicts that the powder material is always compacted to $V/V_0=1$. In that case when D approaches 1, $\delta V/V_0$ and therefore δV has to go to zero. However, if D approaches 0, $\delta V/V_0$ and consequently δV may be infinite in order that U_s^p and P^p are predicted within 5% accuracy. The lower the initial powder density, the less accurate V ought to be predicted. In fact, when D approaches 0, the error in predicting V can be infinite in order to predict U_s^p and P^p exactly. In addition, it can be concluded from Fig. 1 that for low density powders the accuracy of a calculated V^p value cannot be checked by making a comparison between theoretical U_s^p vs u_p values with experimental shock wave U_s vs u_p data.

The above-mentioned analysis is verified by proposing a novel model, especially valid for the prediction of shock compaction of powder material with initial density less than 50% to fully dense material. It is assumed that the specific volume behind the shock wave equals the zero pressure solid specific volume, $V=V_0$. As a consequence the predicted shock wave velocity and shock wave pressure are modified accordingly

$$U_s^p=\frac{V_{00}u_p}{V_{00}-V_0}=\frac{u_p}{1-D}, \tag{6}$$

$$P^p=\frac{U_s^p u_p}{V_{00}}=\frac{u_p^2}{V_{00}-V_0}=\frac{D}{1-D}\rho_0 u_p^2, \tag{7}$$

where V_0 equals $V+\delta V$ and ρ_0 is the specific mass, $\rho_0=1/V_0$. Equations (6) and (7) are wrong for $D=1$, solid material compaction, since $\delta V/V_0$ has to be minimum (Fig. 1). As D goes to 0, Eqs. (6) and (7) hold since $\delta V/V_0$ may approach infinity in order that U_s^p and P^p are within a 5% accuracy. According to the model presented previously,[1,2] Eqs. (6) and (7) are correct for powder material for which D is described as

$$D=\frac{\Gamma(V_0)}{2+\Gamma(V_0)}, \tag{8}$$

where $\Gamma(V_0)$ represents the zero pressure Grüneisen parameter at room temperature.

Between $D=0$ and D is equal to Eq. (8) it seems that Eq. (6) predicts U_s^p too low, as compared with calculated U_s curves of Cu in a U_s vs u_p map at various densities.[2] However experimental U_s values are lower than predicted.[2] This is due to an internal energy leakage through the already compacted material which is caused by collision of single particles on the shock front surface. It means that $E-E_{00}<\frac{1}{2}u_p^2$, so that Eq. (3) fails for low initial powder density materials. Therefore Eqs. (6) and (7) seem to be promising and a 5% U_s^p error test on more materials is appealing.

With Eq. (6) U_s^p vs u_p lines are calculated and compared with experimental values of various materials: Fe, Cu, Al, C,
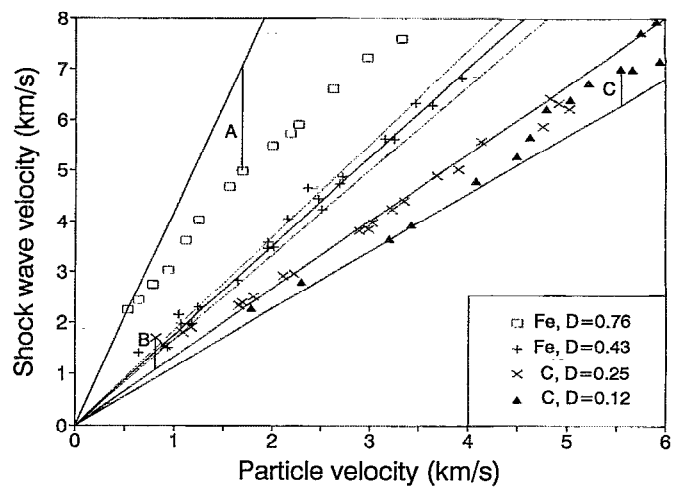

FIG. 2. Theoretical shock wave velocity U_s^p vs particle velocity u_p as compared with experiments for different initial powder density of various materials. For Fe, $D=0.43$ the 5% U_s^p error boundary is depicted. Regions: A, solid compression wins over thermal volume expansion; B, thermal expansion wins over solid compression; C, the material is not fully compacted.

UO_2, Ce_2O_3, SiO_2, NaCl, and polystyrene. For Fe, $D=0.76$ and $D=0.43$ and for C, $D=0.25$ and $D=0.12$; the calculated lines and the experimental U_s vs u_p data are depicted in Fig. 2. The 5% U_s^p error boundaries are given for $D=0.43$.

Discrepancies between theory and experiment appear for the following reasons. At relatively high u_p where the density is high and the shock wave velocity U_s is lower than predicted, this is due to the fact that solid compression wins over thermal volume expansion (Fig. 2, "A"). At high u_p when D is low and U_s is higher than predicted this is because of thermal volume expansion wins over solid compression (Fig. 2, "C"). At high temperature and relatively low pressure the material might completely evaporate (Fig. 2 C). In the situation at low particle velocity u_p where D is low and U_s turns out to be higher than predicted, deviations occur because the material is not fully compacted (Fig. 2 "B") or because the powder has not been gas evacuated (Fig. 2, B).

For all the materials mentioned above, for different initial powder density, the exact value of u_p has been obtained for which the U_s^p value of Eq. (6) and therefore P^p starts to deviate by 5% from the experimental data. These values obtained are displayed in a density D vs u_p map in Fig. 3. It can be seen that for $D<0.50$ for u_p up to 5 km/s a large U_s vs u_p area can be predicted within 5% accuracy by Eq. (6), area 1. In areas 2–5 Eq. (6) starts to fail, i.e., the error in predicting U_s^p is larger than 5%.

In area 2, solid compression dominates too much so that $V<V_0$. In areas 3 and 4, thermal expansion dominates too much so that $V>V_0$. In Area 4 (not calculated) the compacted material de-gasifies completely. This is illustrated by the following analysis: For $D=0$, $P=0$, the internal energy increase of a single particle colliding onto a flat surface of the same material is about $E-E_0<\frac{1}{2}u_p^2$ instead of $\frac{1}{2}u_p^2$. When one particle collides on the shock front surface, due to plastic deformation the thermal energy increase is high, say
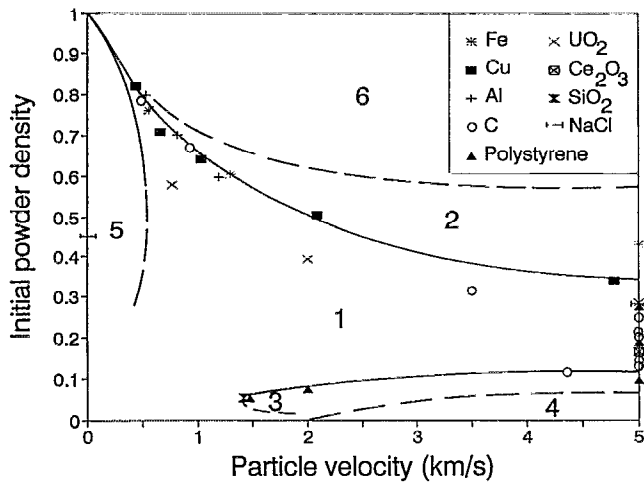
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FIG. 3. D vs u_p map showing the area 1 for which the novel model predicts U_s^p (and so P^p) within 5% error. Area 2: U_s^p differs more than 5% from experiment. The material behind the shock wave is compacted to $V < V_0$. Area 3: U_s^p differs more than 5% from experiment. The material behind the shock wave is compacted to $V > V_0$. Area 4: Complete gasification (area estimated). Area 5: U_s^p differs more than 5% from experiment, $V > V_0$. The material is either not completely compacted or the powder has not been gas evacuated (area estimated). Area 6: U_s^p differs more than 10% from experiment. The material behind the shock wave is compacted to $V < V_0$.
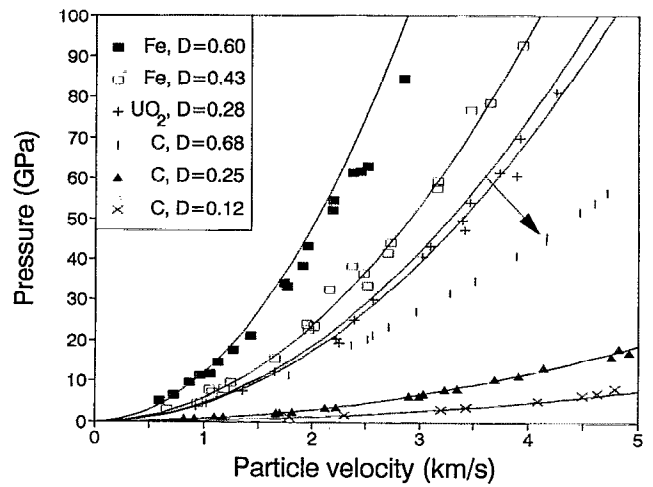
FIG. 4. Pressure P vs particle velocity u_p for different materials at various initial powder densities. For $D < \pm 0.50$, the theory agrees well with experiments. For C, $D = 0.68$ the arrow indicates the discrepancy between theory and experiment. For Fe, $D = 0.60$ and C, $D = 0.68$ the calculated values for P^p (and therefore U_s^p) start to differ more than 5% from experiment above $u_p = 1.3$ km/s and $u_p = 0.9$ km/s, respectively.

$E_t = \frac{1}{4} u_p^2$. Suppose that for gasification of a material at zero pressure a temperature increase of $\delta T = 2500$ °C is needed. Then the flyer-plate velocity for which this happens is given by

$$u_p = (4 C_p \delta T)^{1/2}. \tag{9}$$

Taking a mean value for the specific energy of $C_p = 400$ J/kg K, gasification occurs for $u_p > 2000$ m/s.

In area 5 (not calculated) the model fails as the powder is not fully compacted or the powder has not been fully gas evacuated. Suppose $P = 5$ GPa is needed to compact a powder to full density. Then area 5 is bounded by the $P = 5$ GPa curve when D approaches unity. For D goes to 0 it does not matter if the powder is compacted to full density or not so that area 5 has a lower boundary for D greater than 0.

Finally, in Fig. 4, the predicted pressure [Eq. (7)] is depicted in comparison with experiment, again showing the accuracy of the novel model. For UO$_2$ with increasing u_p, the pressure becomes relatively high as a result of its extreme high specific mass, $\rho_0 = 10.3e3$ kg/m³. As a consequence at $D = 0.39$, the error in Eq. (6) becomes larger than 5% at relatively low u_p (Fig. 3).

In conclusion it turned out to be possible to predict the shock wave velocity as well as the shock pressure using generally applicable formulas. By error analyses it has been shown that the influence of the predicted volume behind the shock wave on shock wave velocity and shock pressure decreases with decreasing initial powder density. The new model has been compared with shock data of various materials: Fe, Cu, Al, C, UO$_2$, Ce$_2$O$_3$, SiO$_2$ (quartz), NaCl, and polystyrene. It is concluded that the model holds in particular for initial powder densities of less than 50% and for flyer-plate velocities up to 50 km/s.

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[3] Y. B. Zel'dovich and Y. P. Raizer, Physics of Shock Waves and High Temperature Hydrodynamic Phenomena, edited by W. D. Hayes and R. F. Probstein (Academic, New York, 1966), Vol. 2, p. 712.
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