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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: Fe, Cu, Al, C, UO2, Ce2O3, SiO2 (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 model1,3 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

\[ U_s = \frac{V_{00}u_p}{V_{00} - V}, \]

\[ P = \frac{u_p^2}{V_{00}} \frac{V_{00} - V}{V_{00}}, \]

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

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 \( \delta V \) 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 \( \delta V \) 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 \( \delta V \), for each \((V, V_{00})\), is calculated from

\[ \text{err} = \frac{1 - \frac{U_s^p}{U_s}}{1 - \frac{P^p}{P}}, \]

By substitution of Eq. (1) and the corresponding equation of \( U_s^p \) into Eq. (4), \( \delta V \) normalized to \( V_{00} \), can be written as

\[ \delta V = \frac{\text{err}}{1 - \text{err}} \left( V - \frac{V_{00}}{V_0} \right), \]

where \( V_{00}/V_0 \) 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., \( V = 0.7 V_0 \) or \( V = 1.3 V_0 \), \( \delta V/V_0 \) does not change much.
In Fig. 1 the $\delta V/V_0$ vs $D$ relationship is displayed for various values of $\text{err}$. In addition, the effect of the specific volume behind the shock wave is depicted. The accuracy in the determination of $U'_p$ and $P'_p$ is chosen to be 5% so that $\text{err} = 0.05$, $\text{err} = 0.10$ and $\text{err} = 0.15$ 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 $\delta V$ has to go to zero. However, if $D$ approaches 0, $\delta V/V_0$ and consequently $\delta V$ may be infinite in order that $U'_p$ 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 $U'_p$ and $P'_p$ exactly. In addition, it can be concluded from Fig. 1 that for low density powders the accuracy of a calculated $V'$ value cannot be checked by making a comparison between theoretical $U'_p$ 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

$$U'_s = \frac{V_0 u_p}{V_0 - V} = \frac{u_p}{1-D},$$  

(6)

$$P'_p = \frac{u'_p u_p}{V_0} = \frac{u^2}{V_0 - V} = \frac{D}{1-D} \rho_0 u^2,$$  

(7)

where $V_0$ equates to $V+\delta V$ and $\rho_0$ 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 $U'_p$ and $P'_p$ are within 5% accuracy. According to the model presented previously, Eqs. (6) and (7) are correct for powder material for which $D$ is described as

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

(8)

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

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 $U'_p$ 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 $U'_p$ 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 $E-E_0<\frac{3}{2}u_p^2$ 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
FIG. 3. D vs u_p map showing the area 1 for which the novel model predicts \( u'_p \) (and so \( P'_p \)) within 5% error. Area 2: \( u'_p \) differs more than 5% from experiment. The material behind the shock wave is compacted to \( V < V_0 \). Area 3: \( u'_p \) 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: \( u'_p \) 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: \( u'_p \) differs more than 10% from experiment. The material behind the shock wave is compacted to \( V < V_0 \).

\[ E_r = \frac{1}{2} u_p^2. \] Suppose that for gasification of a material at zero pressure a temperature increase of \( \Delta T = 2500 \text{ } ^\circ\text{C} \) is needed. Then the flyer-plate velocity for which this happens is given by

\[ u_p = \left( 4 C_p \Delta T \right)^{1/2}. \] (9)

Taking a mean value for the specific energy of \( C_p = 400 \) J/kg K, gasification occurs for \( u_p > 2000 \text{ m/s} \).

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 \( \text{UO}_2 \) with increasing \( u_p \), the pressure becomes relatively high as a result of its extreme high specific mass, \( \rho_0 = 10.3 \text{e}3 \text{ kg/m}^3 \). 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, \( \text{UO}_2 \), \( \text{Ce}_2\text{O}_3 \), \( \text{SiO}_2 \) (quartz), \( \text{NaCl} \), 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.