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METHOD FOR DETERMINING THE PRESSURE REQUIRED FOR SHOCK COMPACTION OF POWDERS

A. Ferreira and M. A. Meyers

Departamento de Engenharia Mecânica e de Materiais
Instituto Militar de Engenharia
Praça General Tibúrcio nº 80, Rio de Janeiro, RJ, 22290, Brasil

Center of Excellence for Advanced Materials
University of California
San Diego, La Jollá, CA 92093, U.S.A.

A model for prediction of the pressure required to shock consolidate a general porous material is presented. The energy required to shock consolidate the material is computed by calculating the various contributions: collapse of voids to densify the material (plastic deformation work), melting of interparticle regions, and generation of defects (dislocations) in shock hardened regions. Based on the total energy involved and by applying the Mie-Grüneisen equation of state to the porous material one can predict the pressure required to consolidate the powder (at a given distension). The general implications of the analysis are presented and discussed. These calculations complement the method developed by Schwarz et al. [1] That predicts the minimum pulse duration for shock consolidation.

I. INTRODUCTION

It is well established that interparticle melting plays an important role in the bonding that occurs between the powder particles in shock compaction of metals. In ceramics, on the other hand, the intense pressure and surface heating might be sufficient to ensure bonding between particles. Gourdin [2] calculated the energy deposition during shock compaction and concluded that most of it is expended in the melting of interparticle layers. Both Schwarz et al. [1] and Gourdin [2, 3] developed energy deposition models at the particle surfaces, which predicted melting fractions in shock consolidated materials. While the models proposed by Schwarz et al. [1] and Gourdin [2,3] are predictions of shock consolidation parameters for soft materials, they do not incorporate the strenght effect, thay play an increasingly important role as the strenght increases. Figure 1 shows that there exist a linear relationship between the experimental pressure required for consolidation and the yield strenght (Y) of the starting material. One can note that pressure necessary to consolidate the material increases as yield strength increases, indicating that the strength of the material has significant influence in the consolidation process.

II. APPROACH

The energy developed during the shock consolidation process is dissipated under several mechanisms. Although all mechanisms occur simultaneously , Figure 2 schematically separates the different processes taking place during shock consolidation process. As the shock wave progresses, void collapse process occurs and maximum densification is obtained. Bonding among the particles is provided by melting of a thickness t in the interparticle region and its subsequent resolidification. At same time, as the shock wave progresses, defects are being generated in the particle interior by the passage of the shock wave, whose amplitude significantly exceeds the dynamic yield strength. Shock-induced defects include point defects, dislocations, twins, and phase transformations. At the final stage the particle material acquires a residual velocity that is reladed to the kinetic energy transferred to the material. Figure 3 schematically shows the pressure-volume diagram in which compares the specific energy behind the shock wave in a solid and porous materials.

The pressure required to shock consolidate a porous materials will be estimated from the energy expended in this process. Based on the several sources of energy dissipation, one can therefore set up the following equation:

$$E_T = E_{v.c} + E_m + E_d \tag{1}$$

where E_T is he total energy involved in the shock consolidation process, $E_{v.c}$ is the energy necessary to collapse the voids, E_m is the energy due to melting process, E_d is the energy of deformation and is related to shock hardening process.

III. FORMULATION

A. VOID COLLAPSE ENERGY

The description of the mechanical response of the porous material will be based on Carroll and Holt's theory [4]. The relative values of the internal radius (a) and of the external radius (b)(Figure 2) define the average distention of the material ($\alpha = b^3/b^3-a^3$). The distention ratio (α) is thus defined [4] as the relation between the total volume (V) and the volume of solid material (V_s). Based on the hollow-shere model the energy involved in the void collapse process has following expression [4]:

$$E_{v.c} = \frac{2}{3} Y V_s \{[\alpha_0 \ln\alpha_0 - (\alpha_0 - 1) \ln(\alpha_0 - 1)] - [\alpha\ln\alpha - (\alpha - 1)\ln(\alpha - 1)\} \tag{2}$$

where α is the final distention, α_0 is the initial distention, Y is the yield strength, V_s is matrix volume, $E_{v.c}$ is the total energy or the change in internal energy that is involved in the densification process. In this calculations it was assumed that the final density of the material after passage of the shock wave is 98% of the theoretical density. This value is in agreement with values described by Gourdin [2].

B. MELTING ENERGY

Melting requires the addition of an extra energy. The expression of the required energy necessary to produce a given melting fraction can be written in the following form [1]:

$$E_m = (\bar{c}_p(T_m - T_0) + H_m]L \qquad (3)$$

where $\bar{c}_p$ is the average value of specific heat, H_m is the latent heat of fusion, L is the mass fraction melted , T_m is the melting temperature of the solid material, and T_0 is the initial temperature. This previous expression does not take into consideration the raise of the initial temperature due to plastic deformation work that is done when the material is densified during the void collapse process ($\Delta T = E_{v.c}/\bar{c}_p$). One can write the final expression for melting energy as follows:

$$E_m = [\bar{c}_p(T_m - T_0 - \frac{E_{v.c}}{\bar{c}_p}) + H_m]L \qquad (4)$$

The energy for melting is treated separately from the void collapse energy because a great deal of redundant plastic deformation (jetting, friction) takes place in shock compaction , leading to additional energy deposition. According to Gourdin [2] the thickness of melt layer ranges from 0 to 2.5 μm. If one considers that for obtaining a good compaction and mechanical properties the particles surface should have a layer of melting of constant thickness, the melting fraction for monosized spherical powders can be expressed as:

$$L = \frac{V_m}{V_T} = 1 - [\frac{D_p - 2t}{D_p}]^3 \qquad (5)$$

where V_m is the melted volume, V_T is the total volume of the particle, D_p is the particle diameter and t is the thickness of the melt layer. The thickness of melting layer obtained by Gourdin [2] provides a guideline for the fraction of melting needed. In the computations that follow, it will be assumed that metals require an average melt layer of 1.5 μm, while ceramics do not require interparticle melting.

C. DEFORMATION ENERGY

The energy associated with dislocations generated by shock wave passage can be estimated from the energy of a dislocation line [5]:

$$E_d = \left(\frac{Gb^2}{10} + \frac{Gb^2}{4} \ln \frac{\rho_d^{-1/2}}{5} \right) \frac{\rho_d}{\rho_0} \qquad (6)$$

where G is the shear modulus, b is the Burgers vector, ρ_d is the dislocation density, and ρ_0 is the density of the consolidated material. The density of the consolidated material takes part in order to obtain the specific energy. According to the literature [6,7] one finds that the dislocation density for shock loaded materials in the pressure range where shock consolidation occurs is approaximatelly equal to $5x10^{10} cm^{-2}$. This average value will be used in the calculations.

IV. RESULTS AND DISCUSSION

The pressure calculated using the previous formulation will be compared with experimental results. Figure 4 shows the total energy required for shock consolidation as a function of the distention. From this plot one can note that for high strength materials, such as Ti_3Al, the void collapse energy dominated the process, while for low strength materials, such as Al, In-718, and Markomet 1064 the melting energy controls the process. The other materials present an equilibrium between both types of energy.

With help of the Mie-Grüneisen equation of state for porous material and the release isentrope curve, the relationship between shock pressure and energy as a function of distention can be established. The detais of this calculations are described elsewhere [8]. The required pressure for shock compaction of different powder materials was calculated at several distentions and same particle diameter (40 μm), in which the hardness values range from 1.2 GPa to 98 GPa from these results one can obtain a master plot. The pressure vs hardness curves were fitted to a best straigbh line, as shown in Figure 5. The results show that as distention decreases, higher pressure is required to shock consolidate the material. It is also shown that at same melting fraction (same particle diameter) and at same distention, the greater is the strength the greater is the pressure required for shock compaction. Thus, as a first approximation, this calculations can be used as a starting point for prediction of the shock consolidation pressures. However, it is worth commenting that is a very first initial idea for prediction of the pressure values. Some simplications were introduced in the calculations in order to become easier to solve a complex phenomena. However, these simplifications do not invalidate the basic idea of the method, and the unknown inherent to the shock consolidation process has already a great degree of incertain.

V. CONCLUSIONS

The model based on energy deposition predicts shock consolidation pressures that are a function of particle size, powder strength, and distention. The predictions of the model are in fair agreement with experimental results and therefore the calculational procedure can serve as a guide in the prediction of shock consolidation pressures.

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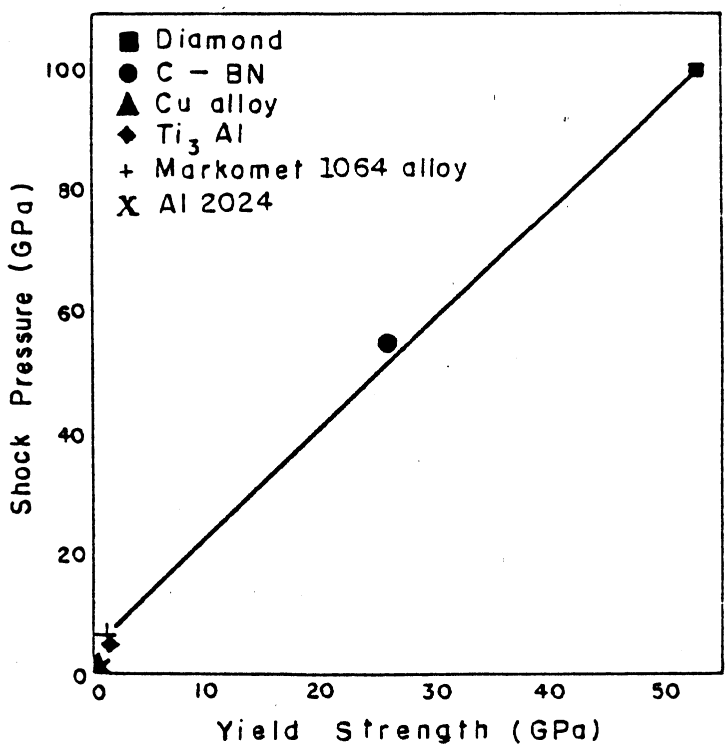

Figure 1 - Correlation between yield stress and experimental pressure required for shock consolidation.

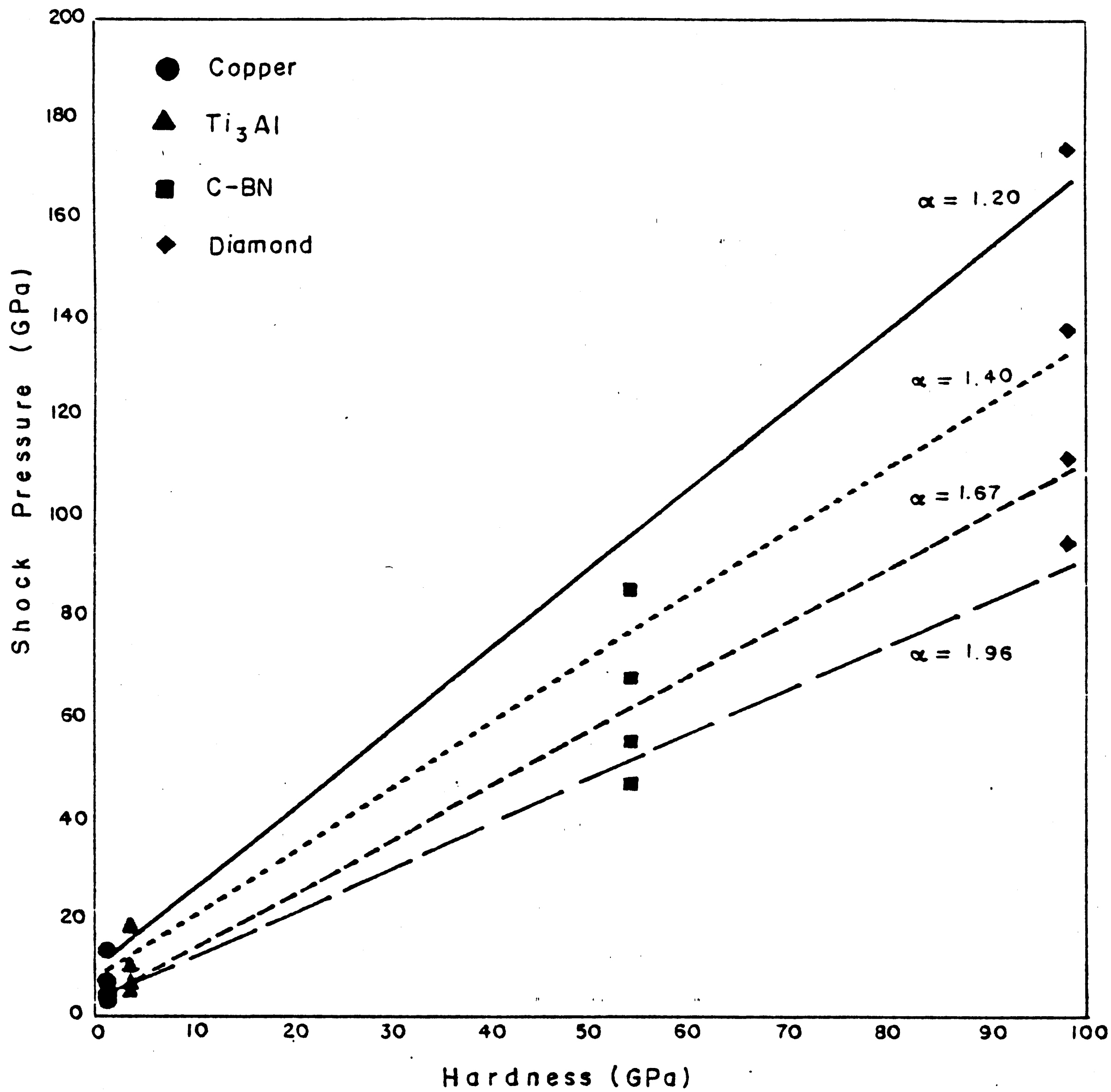

Figure 5 - Pressure required for shock consolidation vs hardness at several distentions.