SHOCK COMPACTION OF MOLYBDENUM POWDER

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Incident shocks varying from 9 to 12 GPa and 25 μs duration, impinging on porous pure Mo (99.99%) powder of dimension 1.4, are found to produce compacts of at least 99.4% of crystal density. Although recovered samples are consolidated and exhibit diamond pyramidal hardness of ~330 to 400, the particles do not appear to be well bonded. Among several possible models for producing a melt layer on particles we propose a dynamic frictional model. The shock pressures required to produce a Si-like film of molybdenum material as a result of dynamic friction varies from 11 to 100 GPa for grain sizes of 100 to 10 μm.

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1. INTRODUCTION

The study of the physics of shock compaction of refractory metals such as Mo is interesting in that it yields insight into the dynamic compression of porous media in general, as well as, providing tests of theories of consolidation. Moreover, the compaction and possible consolidation of refractory metal powders via shock wave in the future lead to a technologically useful process. Recently, Murr et al. [2] has reported some optical and electron microscopy and hardness of shock compacted Mo. They discovered that explosively compacted (and hardened) Mo retained in excess of 300 diamond pyramidal hardness (DPH) at high temperatures.

The present report describes the results of some exploratory compaction experiments carried out by projectile impact. Optical microscopy and microhardness measurements of the resulting samples were carried out. In addition, we present a theoretical model to predict the onset of the shock pressure regime over which shock consolidation is predicted to occur.

2. EXPERIMENTAL DETAILS

All lots of powdered Mo, <35 mesh (grains 45 μm), were pressed into stainless steel sample containers to a density of 0.7 times crystal density or 7.0 g/cm³ corresponding to a compaction, m., of 1.4. The samples were evacuated to <50 μm Hg (air pressure) and impacted with 304 stainless steel projectiles at speeds from 1 to 2 m/s. Only three experimental assemblies (Fig. 2) shocked in the 8.0 to 11.8 GPa pressure range (Table I). Yielded samples which were suitable for microscopy and hardness measurements. Shock pressures in the samples were calculated using the impulse match method and a fit of Mo equation of state parameters [2] to the theoretical fit for porous media of Simons and Legoer [3].

50 μm

1. Micrograph of initial Mo powder (35 mesh).

Table 1. Shock recovery experiments, 314 mesh powdery Mo.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Shock Pressure in Stainless Steel (GPa)</th>
<th>Initial Shock Pressure in Diamond Pyramid (GPa)</th>
<th>Final DPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>19.0</td>
<td>8.0</td>
<td>304</td>
</tr>
<tr>
<td>133</td>
<td>20.0</td>
<td>10.2</td>
<td>398</td>
</tr>
<tr>
<td>144</td>
<td>25.0</td>
<td>11.0</td>
<td>335</td>
</tr>
</tbody>
</table>
3. RESULTS

Although some of the samples demonstrate plucking out of particles upon polishing sections of recovered material, the post-shock density of these was 10.15 ± 0.04 g/cm³, which is close to crystal density of 10.286 g/cm³.

From the most highly shocked, recovered samples (Fig. 11) demonstrated case grain refinement. However, the mechanical properties were such that complete interparticle welding had not taken place. This contrasts to the behavior of a similar distension rapid solidified steel powder [5] which demonstrated complete interparticle welding at 18 GPa (Fig. 4).

4. Micrograph of 9310 steel powder (50μm) shock consolidated to 18 GPa.

4. THEORY

Previously [5], we have modeled the shock consolidation process as one in which a thin film of melt is produced by possibly grain boundary sliding during shock compression at the shock front. A minimum shock pressure required for completion, as defined by the level of allotropic tensile strength can correspond to several microscopic processes including:

(1) Production of a zone melt layer via dynamic friction.

(2) Deformation behavior such that more irreversible work is near the particle surfaces rather than in the interior of the particle.

(3) Conduction of heat away from particle surfaces during shock compression.

(4) The generation of sufficient metal melt such that:

(a) Surface oxide coatings on the grains are removed and/or ingested in the melt, or
(b) The melt coats and fills internal voids and cracks in the compacted metal.

We propose a theory for describing Process #1 (above).

Process (4) can partially be described with a simple expression for the mass fraction of melt:

\[ L = \frac{P V_0 (m+1)}{2 [C_p (T_0 - T_f) + V_h]} \]  \hspace{1cm} (1)
where, complete melting corresponds to L-1. Here $v_e$ is specific volume of the solid, $a$ is distance. $C_w$ is specific heat, $T_0$ is melting point, $T_f$ initial temperature and $H_f$ is the heat of fusion.

Rowden and Tabor [6] have demonstrated that when metals slide at speeds of 10-2 m/sec, a film of liquid forms along the contact and the coefficient of friction, $u$, drops to 0.2. We assume that during the process of sneak-up of the porous media for a time, $t_{cp}$, of the order of that required for the free-surface of a grain to collide with the next grain, the mean distance traveled, $x$, is given by

$$x = \frac{v_{cp}}{3}$$

where $d$ is the grain size and $v_{cp}$ is the free surface velocity, hence

$$t_{cp} = \frac{d}{v_{cp}}$$

The energy deposited per unit mass by grain boundary friction, $t_f$, is

$$t_f = \frac{u_{cp}}{v_{cp}} (H_f) \frac{v}{(v_{cp})}$$

where $v/(v_{cp})H_f$ is the surface area per unit mass. (13) is the mass fraction of material in the surface “friction”, or shear, zone, of thickness, $t_f$, than we can write that the criterion for shock-induced surface melting is

$$\mu_{cp} = \frac{v}{(v_{cp})} \frac{v}{(v_{cp})}$$

or

$$P \geq \frac{3a}{(1 - T_0 + T_1) C_p + H_f}$$

In addition to requiring a shock pressure greater than specified by Eq. 6, we also require that the duration of the shock, $t_d$, be greater than the time required for the melt to solidity via heat conduction into the solid interior of the grain. The shock duration to solidity a mass fraction of melt specified by Eq. 6 is given by

$$t_d = \sqrt{\frac{6q}{C_p \left[(1 - T_0) C_p + H_f \right]^2}}$$

where $q$ is thermal diffusivity.

In the use of shock melting on surfaces to correspond to $P = 1$ GPA, $m = 1.6$ for $n = 0.8$. We infer a shear zone thickness of $s = 1.26$ m for Eq. 6.

Using this value of $s = 1.26$ m for $n$ to infer a possible mean adiabat for melting, yields using Eq. 6, the values of critical pressure for different values of $n$ and $a$ are given in Table 2. Notably, the present experiments for $d < 45$ m were conducted slightly below the shock stress levels required to produce melt, and hence consolidation. The present model also requires freezing of the shock melted surface coating on the grains prior to unloading.

Table 2. Calculated Shock Pressure (GPa) for Consolidating Powders No.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>1.4</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size (µm)</td>
<td>100</td>
<td>10.8</td>
</tr>
<tr>
<td>50</td>
<td>21.5</td>
<td>18.4</td>
</tr>
<tr>
<td>10</td>
<td>107.6</td>
<td>72.0</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Shock recovery experiments carried out at the 12 to 12 GPA range on 1.4 distance No. appear adequate to compact to full density (4-45 m) powders. However, the stress levels are below those calculated to be from 100 to 120 GPa which a frictional heating model predicts are required to consolidate 10 to 50 mm particles. The present model indicates that for powders having a distance of 1.4-12 GPA, shock pressures of 50 to 72 GPa are required to consolidate No. powders in the 50 to 10 µm range.

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REFERENCES


