General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)
SHOCK COMPACTION OF MOLYBDENUM POWDER

Thomas J. Ahrens, D. Kostka, T. Vreeland, Jr., R. B. Schwarz*, and P. Kasiraj
California Institute of Technology
Pasadena, CA 91125
*Materials Science and Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

September 1983

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Submitted to the Proc. of the 3rd APS Conf. on Shock Waves in Solids, Santa Fe, New Mexico (North Holland, 1983).
SHOCK COMPACTION OF MOLYBDENUM POWDER

Thomas J. Ahrens, D. Kostka, T. Vreeland, Jr., R. B. Schwarz* and P. Kasiraj

California Institute of Technology, Pasadena, California 91125

Incident shocks varying from 9 to 12 GPa and 2us duration, impinging on porous pure Mo (100 µm) powders of distension 1.4, are found to produce compacts of at least 99.4% of crystal density. Although recovered samples are consolidated and exhibit diamond pyramid 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 1-µm film of molten material as a result of dynamic friction varies from 11 to 108 GPa for grain sizes of 100 to 10 µm.

*On leave from MST Div., Argonne National Laboratory, Argonne, IL 60439.

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 may in the future lead to a technologically useful process. Recently Murr et al. [1] 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 pyramid 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.

Aliquots of powdered Mo, -325 mesh (grains <45µm) (Fig. 1) were pressed into stainless steel sample containers to a density of 0.7 times crystal density or 7.0 g/cm³ corresponding to a distension, m, of 1.43. The samples were evacuated to <50µm Hg (air pressure) and impacted with 304 stainless steel projectiles at speeds from 1 to 2 km/sec. Only three experimental assemblies (Fig. 2) shocked in the 8.8 to 11.8 GPa pressure range (Table 1) yielded samples which were suitable for microscopy and hardness measurements. Shock pressures in the samples were calculated using the impedance match method and of Mo equation of state parameters [2] the theoretical form for porous media of Simons and Legner [3].

Table 1. Shock recovery experiments, m=1.4 powdered Mo.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Shock Pressure in Stainless Steel (GPa)</th>
<th>Initial Diamond Pyramid Sample (GPa)</th>
<th>Shock Pressure in Pyramid Sample (GPa)</th>
<th>Diamond Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>612</td>
<td>19.0</td>
<td>8.3</td>
<td>389</td>
<td></td>
</tr>
<tr>
<td>613</td>
<td>20.0</td>
<td>10.2</td>
<td>398</td>
<td></td>
</tr>
<tr>
<td>614</td>
<td>25.0</td>
<td>11.8</td>
<td>333</td>
<td></td>
</tr>
</tbody>
</table>

1. Micrograph of initial Mo powder (325 mesh).
2. Cross-section of target recovery assembly.

3. RESULTS

Although some of the samples demonstrate plucking out of particles upon polishing sections of recovered materials, the post-shock density of these was $10.15 \pm 0.04 \text{ g/cm}^3$ which is close to crystal density of $10.206 \text{ g/cm}^3$.

Even the most highly shocked, recovered samples (Fig. 3) demonstrated some 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 [4] which demonstrates complete interparticle welding at 18 GPa (Fig. 4).

4. Micrograph of 9310 steel powder (50um) 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 compaction at the shock front. A minimum shock pressure required for compaction, as defined by the level of ultimate 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 grain 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:

$$L = \frac{P V_0 (m-1)}{2 \left[ C_p (T_m - T_0) + H_0 \right]}$$  \hspace{1cm} (1)
where, complete melting corresponds to \( L = 1 \). Here \( V_0 \) is specific volume of the solid, \( m \) is distension, \( C_p \) is specific heat, \( T_m \) is melting point, \( T_o \) initial temperature and \( H_m \) is the heat of fusion.

Bowden and Tabor [6] have demonstrated that when metals slide at speeds of >0.5 km/sec, a film of liquid forms along the contact and the coefficient of friction, \( \mu \), drops to ~0.1. We assume that during the process of crush-up of the porous media for a time, \( \Delta t \), of the order of that required for the free-surface of a grain to collide with the next grain, the mean distance traveled, \( g \), is given by

\[
g = \frac{(m-1)}{d} \cdot \Delta t \quad (2)
\]

where \( d \) is the grain size and \( u_{FS} \) is the free surface velocity. Hence

\[
\Delta t = (m-1) \cdot d / (u_{FS} \cdot 3) \quad (3)
\]

The energy deposited per unit mass by grain boundary friction, \( E_f \), is

\[
E_f = \mu \cdot u_{FS} \cdot (\Delta t) / 3 / [(d+g) \cdot \rho_o] \quad (4)
\]

where \( 3 / [(d+g) \cdot \rho_o] \) is the surface area per unit mass. If \( 3 / [(d+g) \cdot \rho_o] \) is the mass fraction of material in the surface "friction", or shear, zone, of thickness, \( \delta \), then we can write that the criterion for shock-induced surface melting is

\[
\mu \cdot u_{FS} \cdot \Delta t \cdot 3 / [(d+g) \cdot \rho_o] \geq \frac{3 \delta / (d+g) \cdot [(T_m - T_o) \cdot C_p + H_m]}{P} \quad (5)
\]

or

\[
P \geq \frac{3 \delta / (d+g) \cdot [(T_m - T_o) \cdot C_p + H_m]}{\mu \cdot u_{FS} \cdot \Delta t} \quad (6)
\]

In addition to requiring a shock pressure greater than specified by Eq. 6, we also require that the duration of the shock, \( \Delta t \), be greater than the time required for the melt to solidify via heat conduction into the solid interior of the grain. The shock duration to solidify a mass fraction of melt specified by Eq. 1 is given by [5]

\[
t_c > \frac{\pi \cdot d^2}{640_m} \cdot \left[ \frac{P \cdot [V_0 \cdot (m-1)] \cdot H_m}{C_p \cdot [(T_m - T_o) \cdot C_p + H_m] \cdot (T_m - T_o)} \right] \quad (7)
\]

where \( D_m \) is thermal diffusivity.

In the case of iron for which we have found the onset of shock melting on surfaces to correspond to \( P=10 \text{ GPa}, m=1.6 \) for \( d=50\mu m \). We infer a shear zone thickness of \( \delta = 1.02 \mu m \) from Eq. 6.

Using this value of \( \delta = 1\mu m \) for Mo, to infer a possible minimum condition for melting, yields using Eq. 6, the values of critical pressure for different values of \( m \) and \( d \) are given in Table 2. Notably, the present experiments for \( d < 45\mu m \) 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>
<thead>
<tr>
<th>Distension</th>
<th>1.4</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain Size (µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>10.8</td>
<td>7.2</td>
</tr>
<tr>
<td>50</td>
<td>21.6</td>
<td>14.4</td>
</tr>
<tr>
<td>10</td>
<td>107.8</td>
<td>72.0</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

Shock recovery experiments carried out in the 9 to 12 GPa range on 1.4 distension Mo appear adequate to compact to full density (< 45µm) powders. However, the stress levels are below those calculated to be from 100 to ~22 GPa which a frictional heating model predicts are required to consolidate ~10 to 50 µm particles. The present model predicts that for powders have a distension of \( m=1.6 \) shock pressures of 14 to 72 GPa are required to consolidate Mo powders in the 50 to 10 µm range.

Acknowledgments: Supported under NASA Grant NASW3752. R.B. Schwarz partially supported by D.O.E. P. Kasiraj, T. Vreeland, Jr., and D. Kostka are with the W. Keck Laboratory for Engineering Materials, Division of Engineering and Applied Science. T. J. Ahrens is with the Seismological Laboratory. Contribution 3944 Division of Geological and Planetary Sciences.

REFERENCES


