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### SHOCK COMPACTION OF MOLYBDENUM POWDER

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**MASTER**

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## SHOCK COMPACTION OF MOLYBDENUM POWDER

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Incident shocks varying from 9 to 12 GPa and 2 $\mu$ s duration, impinging on porous pure Mo (100  $\mu$ m) powder 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 $\mu$ m film of molten material as a result of dynamic friction varies from 11 to 108 GPa for grain sizes of 100 to 10  $\mu$ m.

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### 1. INTRODUCTION

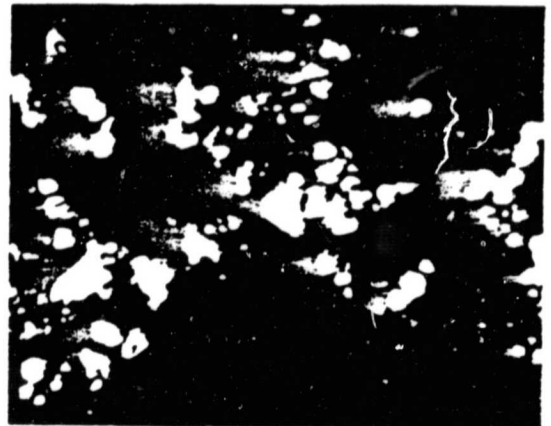
The study of the physics of shock compaction of refractory metals such as Mo is interesting in that it yields insight into the dynamic compression of porous media in general, as well as, providing tests of theories of consolidation. Moreover, the compaction and possible consolidation of refractory metal powders via shock 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 <45 $\mu$ m) (Fig. 1) were pressed into stainless steel sample containers to a density of 0.7 times crystal density or 7.0 g/cm<sup>3</sup> corresponding to a distension,  $m$ , of 1.43. The samples were

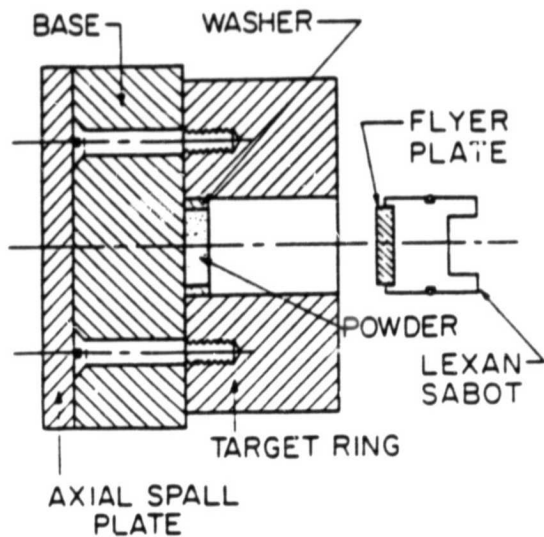
evacuated to <50 $\mu$ m Hg (air pressure) and impacted with 304 stainless steel projectiles at speeds from 1 to 2 km/sec. Only three experimental assemblies (Fig. 2) shocked in the 8.8 to 11.8 GPa pressure range (Table 1) yielded samples which were suitable for microscopy and hardness measurements. Shock pressures in the samples were calculated using the impedance match method and  $\rho$  of Mo equation of state parameters [2]. The theoretical form for porous media of Simons and Legner [3].



1. Micrograph of initial Mo powder (325 mesh).

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

Shot #	Shock Pressure in Stainless Steel (GPa)	Initial Shock Pressure in Sample (GPa)	Diamond Pyramid Hardness
612	19.0	8.3	389
613	20.0	10.2	398
614	25.0	11.8	333

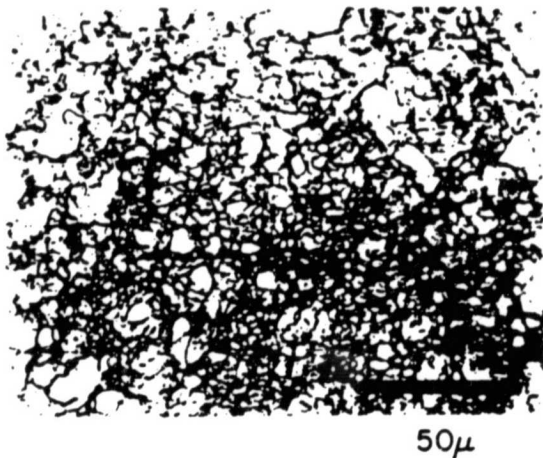


2. Cross-section of target recovery assembly.

### 3. RESULTS

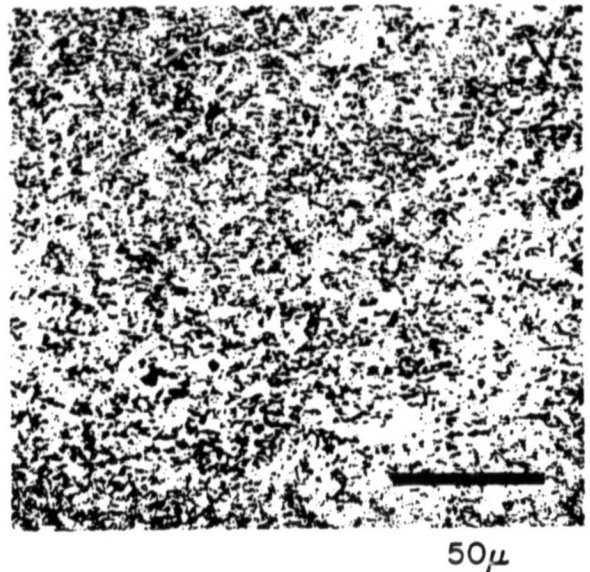
Although some of the samples demonstrate plucking out of particles upon polishing sections of recovered materials, the post-shock density of these was  $10.15 \pm 0.04 \text{ g/cm}^3$  which is close to crystal density of  $10.206 \text{ g/cm}^3$ .

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



3. Micrograph of 1.4 distension Mo powder shock compacted to 11 GPa.

a similar distension rapid solidified steel powder [4] which demonstrates complete interparticle welding at 18 GPa (Fig. 4).



4. Micrograph of 9310 steel powder (50 $\mu\text{m}$ ) 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:

$$L = \frac{P V_0 (m-1)}{2 [C_p (T_m - T_0) + H_m]} \quad (1)$$

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,  $T_0$  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  $\sim 0.1$ . We assume that during the process of crush-up of the porous media for a time,  $\Delta t_c$ , 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

$$g = \frac{(m-1)}{3} d \quad (2)$$

where  $d$  is the grain size and  $u_{fS}$  is the free surface velocity. Hence

$$\Delta t_c = (m-1) d / (u_{fS} 3) \quad (3)$$

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

$$E_f \sim \mu P u_{fS} (\Delta t_c) 3 / [(d+g) \rho_0] \quad (4)$$

where  $3 / [(d+g) \rho_0]$  is the surface area per unit mass. If  $3\delta / (d+g)$  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

$$\mu P u_{fS} \Delta t_c 3 / [(d+g) \rho_0] \geq 3\delta / (d+g) [(T_m - T_0) C_p + H_m] \quad (5)$$

or

$$P \geq \frac{3\delta [(T_m - T_0) C_p + H_m] \rho_0}{\mu d (m-1)} \quad (6)$$

In addition to requiring a shock pressure greater than specified by Eq. 6, we also require that the duration of the shock,  $t_s$ , 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]

$$t_s > \frac{\pi d^2}{64 D_m} \left[ \frac{P [V_0 (m-1)] H_m}{C_p [(T_m - T_0) C_p + H_m] (T_m - T_0)} \right]^2 \quad (7)$$

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  $P=10$  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 2. Calculated Minimum Shock Pressure (GPa) for Consolidating Powdered Mo

Distension	1.4	1.6
Grain Size ( $\mu m$ )		
100	10.8	7.2
50	21.6	14.4
10	107.8	72.0

## 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 ( $< 45\mu m$ ) powders. However, the stress levels are below those calculated to be from 100 to  $\sim 22$  GPa which a frictional heating model predicts are required to consolidate  $\sim 10$  to  $50 \mu m$  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  $10 \mu m$  range.

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## REFERENCES

- [1] Murr, L.E., Tuominen, S.M., Hare, A.W., and Wang, S.-H., Structure and hardness of explosively consolidated molybdenum, *Materials Science and Engineering* 57 (1983) 107-.
- [2] McQueen, R.G., Marsh, S.P., Taylor, J.W., Fritz, J.N., and Carter, W.J., The equation of state of solids from shock-wave studies, in Kinslow, R. (ed.), *High Velocity Impact Phenomena* (Academic Press, 1970), 294-419.
- [3] Simons, G.A. and Legner, H.H., An analytic model for shock Hugoniot in porous materials, *J. Appl. Phys.* 53 (1982) 943-947.

- [4] Kasiraj, P., Vreeland, T., Jr., Schwarz, R.B., and Ahrens, T.J., Shock consolidation of a rapidly solidified steel powder, submitted for publication (1983).
- [5] Schwarz, R.B., Kasiraj, P., Vreeland, T., Jr., and Ahrens, T.J., A theory for the shock-wave consolidation of powders, submitted for publication (1983).
- [6] Bowden, F.P. and Tabor, D., Part II, The Friction and Lubrication of Solids (Oxford Press, 1968), 544 pp.