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DEFORMATION OF CYLINDRICAL CONTAINERS AND CERAMIC POWDERS BY EXPLOSIVE COMPACTION

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Experiments on explosive compaction of an oxide powder layer in a cylindrical container by sliding detonation of ammonite are performed with various thicknesses of the HE and the container and for various materials of the container and the powder. With increase in the loading rate, stepped irregularities appeared and increased in amplitude on the boundaries between the metal and the compacted ceramic layer. The ceramics layer in this case cracked into pieces, which were shifted relative to each other and pressed into the metal surface. The results obtained are explained by features of the compaction of the powder in the container by sliding loading. The strength of the ceramics turned out to be higher than that of the metal of the container, and the ceramics that formed immediately behind the incident shock wave in the powder experienced additional strain.

1. A widely used method of compacting powders by an explosion is axisymmetric loading of powders in cylindrical containers by sliding detonation. Results of loading in this case depend on many factors, both geometrical and physical. Matytsin [1] showed that within the framework of a rigid-plastic model, six independent variables are required to describe the behavior of a container with a powder (to determine stresses and velocities) in the one-dimensional, nonstationary, axisymmetric case. For successful preservation of the powder in the container, it is necessary to undertake special measures, because the tensile stresses originating in a rarefaction wave give rise to cracks in brittle materials such as, for example, oxides. This circumstance hampers the production by explosive compaction of large ceramics samples without cracks.

Prummer [2] was apparently the first who proved that cracks can arise not only in a rarefaction wave but also in a cylindrical container with a powder under the action of compressive stresses. While moving toward the axis, a powder compacted by a shock-wave (SW) can experience a localized surface shear due to maximum tangential stresses at an angle of 45° to the direction of the radius. An adiabatic shear of this type produced by explosive compaction of fast-hardening amorphous alloys was studied in [3–6], where the types of crack originating in a rarefaction wave (radial, transverse, and cylindrical) and in loading (helical) are described.

The present work reports results from experiments on explosive compaction of a cylindrical layer of a powder that indicate the existence of one more factor responsible for the occurrence of shear strains and cracks in ceramics.

2. Powders were loaded in cylindrical containers by an outside charge of 6ZhV ammonite of density 1.1 g/cm^3 by an axisymmetric scheme. Sliding detonation of the high-explosive (HE) layer in contact with the container was initiated by a detonator located on the axis at a distance from the container equal to two or three thicknesses of the layer. In experiment No. 16 (see Table 1), initiation of ammonite was performed by means of an outer 1-mm-thick layer of a prime plastic HE.

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TABLE 1

Loading Conditions and Experimental Results

Experiment No.	Tube material	Thickness, mm		Oxide	Maximum height of steps, mm		Note
		of tube	of HE		on rod	on tube	
1*	St. 3	3.0	10	Al_2O_3	0.02**	0.02**	—
2	»	4.0	10	Al_2O_3	0.02**	0.02**	—
4	»	4.0	20	Al_2O_3	0.05	0.1	The tube cracked
5	»	5.5	20	MgO	0.02**	0.02**	—
6	»	6.0	23	Al_2O_3	0.1	0.1	1–2 steps on the sample
7	Copper	6.0	23	Al_2O_3	0.1	0.1	Ejection of ceramics
8	Duralumin D16	6.0	23	Al_2O_3	0.4	0.8	Tube failed
9	»	6.0	23	MgO	0.02**	0.3	»
10	St. 3	6.0	30	Al_2O_3	0.3	0.3	Ejection of ceramics
11	»	7.0	25	MgO	0.02**	0.02**	»
13	»	5.0	30	SiO_2	0.1	0.1	—
14	»	5.0	30	SiO_2 (c)	0.02**	0.02**	—
15*	»	4.5	25	Al_2O_3	0.5	0.6	—
16*	»	4.5	25 + 1	Al_2O_3	0.25	0.1	—
17*	»	4.5	25	$Al_2O_3 + Al$	0.02**	0.02**	—
18*	»	4.5	25	Al_2O_3	Rod is absent	0.1	Ejection of ceramics
19*	»	4.7	20	MgO	Less than 0.3 (D16)	0.1	—
20*	»	4.7	20	MgO (c)	0.2 (D16)	0.1	—
21	Stainless steel	3.6	10	MgO	Rod is absent	0.02**	—
22	»	3.6	10	Al_2O_3	»	0.02**	—
23	»	3.6	15	MgO	»	0.02**	—
24	»	3.6	15	Al_2O_3	»	0.02**	Ejection of ceramics
25	Copper	6.0	20	Al_2O_3	»	0.02**	—

Notes. *In the experiments, tubes with inside diameter 35.5 mm and length 130 mm were used. **The height of the steps is not greater than the height of traces from the tool used in the fabrication of the container; (c) indicates that preliminary compaction of the powder was performed.

In the first series of experiments, a rod with diameter 15 mm made of steel St. 3 (experiment Nos. 1–17) or D16 Duralumin (experiment Nos. 19 and 20) was placed on the axis of a tube with inside diameter 35.5 or 30 mm and length 130 or 280 mm, respectively. Tubes of metals with various density and strength were used. The material of the containers and the thicknesses of their walls are given in Table 1.

The gap between the tube and the rod was filled with powders of aluminum or silicon oxides with particle sizes of 10–100 and 2–10 μm, respectively, or magnesium oxide having particle conglomerates of size

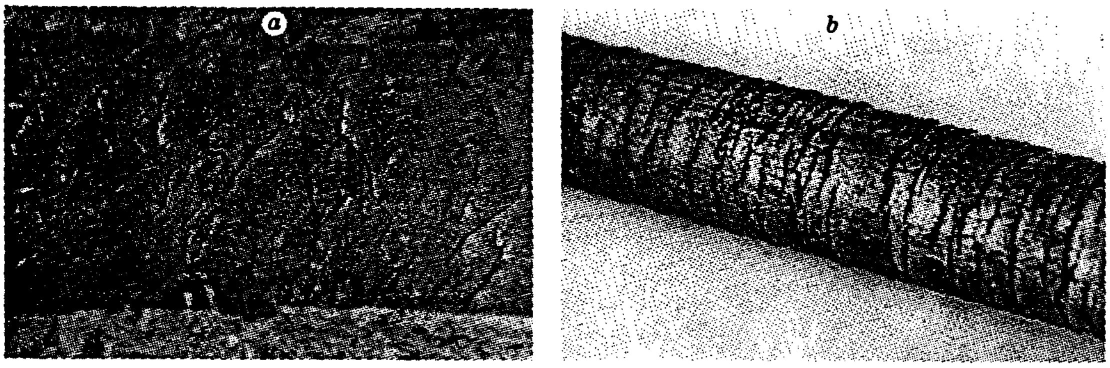

Fig. 1. Strain traces on the surfaces of the tube (experiment No. 9) (a) and rod of Ø 15 mm (experiment No. 8) (b), direction of detonation from left to right.

50–500 μm. (The starting magnesium oxide powder had particle sizes not larger than 1 μm and low bulk density, and, therefore, its density was increased by preliminary compaction of the powder in the cylindrical container by a weak HE charge with subsequent grinding in a spherical mill.) Most of the experiments were carried out with Al and Mg oxides. In experiment No. 17, a mixture of bulk density prepared from aluminum oxide and aluminum powders taken in a mass ratio of 1:1 was compacted.

The powders used were primarily of bulk density (in percent of monolith density): 1.44 g/cm^3 (37%) for aluminum oxides, 1.54 g/cm^3 (42%) for magnesium, and 0.57 g/cm^3 (26%) for silicon. In experiments 14 and 20, silicon oxide was preliminarily compacted to a density of 0.94 g/cm^3 (42%) and magnesium oxide to 2.36 g/cm^3 (66%).

In the second series of experiments, loading was performed without a rod in a tube of St. 3 with inside diameter 35.5 mm (experiment No. 18) or 12Kh18N9T stainless steel with inside diameter 43 mm and length 280 mm (experiment Nos. 21–25). The Al_2O_3 powder used had the same density and particle size as in the first series of experiments and MgO had a particle size of about 1 μm and a density of 1.23 g/cm^3 (34%).

The inner surface of tubes of length 280 mm made of stainless steel was not specially treated. The precision of manufacture of all details is not worse than class 5, and the average height of the surface irregularities was not greater than 10–20 μm.

After loading, the structure of the samples in the longitudinal and cross sections of the container was studied by the naked eye and under a microscope. In addition, the maximum height of the steps that arise on the surface of the tube and the rod upon deformation was determined with a relative error of 20–30% by direct measurements or comparison with an object whose size was known.

3. Upon loading by a 23-mm-thick ammonite layer, a duralumin tube 6 mm thick (experiment Nos. 8 and 9) broke up into parts along the generatrix, and the ceramics practically was not preserved. The traces left by the ceramics on the surface of the tube and the rod were investigated. In experiment No. 4, loading gave rise to cracks in the tube. In experiment Nos. 7, 10, 11, 18, and 24 with copper and steel tubes at great thicknesses of the charge, only part of the ceramics — from 10 to 75% — was preserved. In the remaining experiments, the samples were completely preserved. In experiment No. 19, revealing of steps was hampered because of the strong adhesion of the compacted magnesium oxide layer to the duralumin rod. The loading conditions and results obtained are summarized in Table 1.

After loading, adhesion of the ceramics to the metal was absent as a rule. In some experiments on containers with a rod, the inner surface of the containers and the lateral surface of the rod shows a distinctive texture, usually as uneven discontinuous and, sometimes, intersecting steps (Fig. 1). In the longitudinal microsection made along the axes, the surface profile of the steps frequently was of an asymmetric sawtooth character (Figs. 1b and 2a). The step profile on the surface of the rod was oriented oppositely to that on the surface of the tube (Fig. 1). Etching of the microsections revealed a shear strain of the metal surface layers to a depth of the order of the step height (Fig. 2a), which was probably produced by pressing of the rigid ceramics into the metal. At a rather high loading rate, the rod could also have a surface strain of another

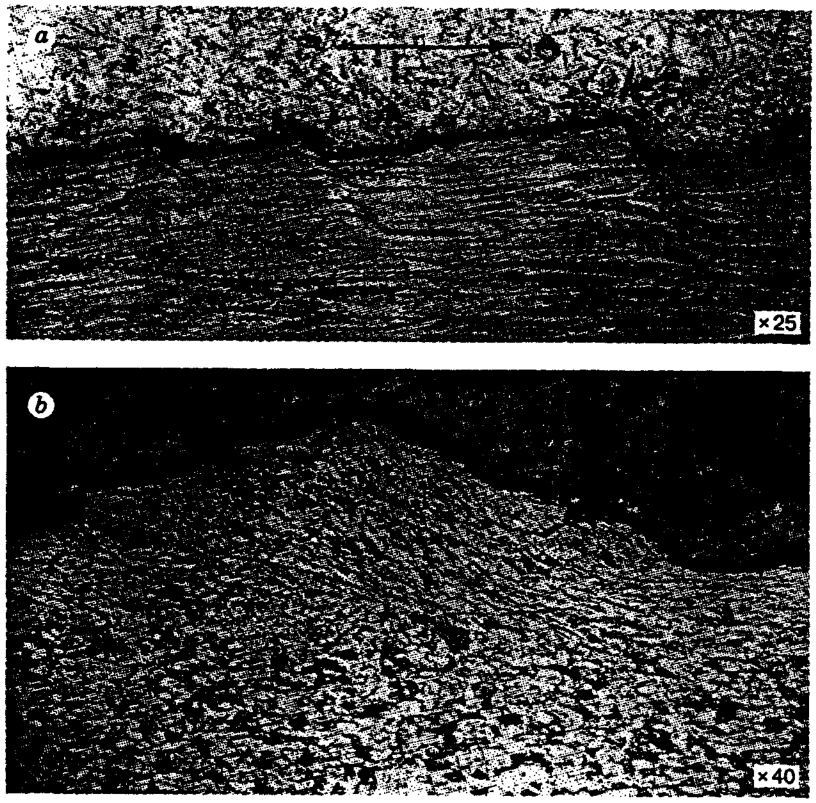

Fig. 2. Strain pattern: (a) in the aluminum tube (Wood alloy is on the top) (experiment No. 9), the arrow shows the direction of detonation; (b) on the rod (experiment No. 8).

direction, which corresponded to the shift of the crest of the step along the axes of the container (Fig. 2b).

In experiments in which the surface profile described above appeared on the metal and the ceramics was completely retained, it turned out that the ceramics cracked to form blocks. After removal of part of the tube, it was seen that the texture of its inner surface reproduced in detail the surface texture of the corresponding segment of the ceramics. Through cracks and shears of contacting surfaces of neighboring blocks in the ceramics corresponded to steps and plastic strains in the metal. In Al_2O_3, through shear cracks were usually at an angle of about 45° to the direction of the radius (Fig. 3). In MgO many through cracks were observed, which were primarily perpendicular to the axis of the container, without signs of shear of neighboring blocks.

In experiments in which the texture is clearly seen, it was observed on the metal of both the tube and the rod, over the entire surface contacting with the powder, except for the end segments of size 3–8 mm. In tubes of length 280 mm, the maximum height of irregularities on the initial segment was on the average about 1.5 times lower than that at the end. Table 1 gives maximum values of the height of irregularities revealed in the experiments.

In microsections made in a plane perpendicular to the axis of the container, helical cracks at an angle of 45° to the radius are found only in experiment No. 21. In the remaining experiments, any regular system of cracks propagating at an angle of 45° to the radius, as in [2, 3, 6], was not revealed.

The remaining results of the experiments can be summarized as follows:

1. The through cracks in the ceramics layer that were accompanied by shear strains in the ceramics and in the metal were frequently oriented in a definite manner relative to the direction of detonation propagation (Fig. 3).

2. In aluminum oxide ceramics, shear strains and cracks arose at lower loading rate and the steps in the metal were on the average higher than those in the ceramics of magnesium and silicon oxides.

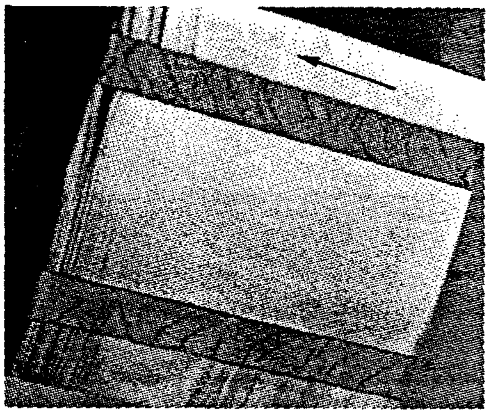

Fig. 3

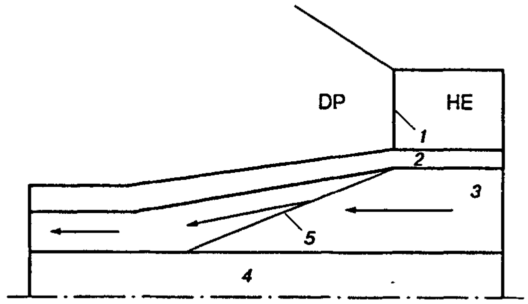

Fig. 4

Fig. 3. Character of cracks in Al_2O_3 (experiment No. 4). The arrow shows the direction of detonation.

Fig. 4. Scheme of motion of ceramics particles when the container is loaded: 1) detonation front; 2) tube; 3) powder; 4) rod; 5) incident shock wave; HE are explosives and DP are detonation products (the arrows show the flow direction).

3. In different experiments, the dimensions of the irregularities (steps) increased as the HE layer thickness increased and as the thickness or mass of the tube decreased; with other conditions being equal, they were larger where the hardness (the yield point) was higher for the ceramics and lower for the metal.

4. The increase in the sliding detonation velocity by coating the surface with a thin layer of a HE whose detonation velocity was about 2 times as high led to a decrease in the height of the step. For the tube, this decrease was more pronounced than for the rod.

5. When the plasticity of the compacted material was increased (by addition of a metal to the ceramics), steps on the tube and the rod and cracks in the compacted layer were not observed after loading.

4. The pressing of the ceramics into the metal with formation of the system of traces and strains described above could have occurred even before the occurrence of tensile stresses, when compressing loads took place behind the SW front. Thus, for traces with rather distinct details to occur, it is necessary that the hardness of the ceramics be higher than the hardness of the metal. Thus, the experiments performed lead to the conclusion that immediately behind the HE front in explosive compaction, the shear strength can be higher for aluminum oxide ceramics than for St. 3 and the strength of magnesium and silicon oxides can approximately correspond to the strength of St. 3 and be higher than the strength of duralumin. In static tests of explosively compacted ceramics [7] under conditions similar to those in the present work, the shear strength limit reaches the following values: 190 MPa for aluminum oxide, 46 MPa for magnesium, and 220 MPa for silicon (for sintered ceramics, these values are 190, 4, and 22 MPa, respectively [8]). However, one should bear in mind that when the strain rate reaches 10^4–10^5 sec^{-1} and load reaches several gigapascals, the strength of metals and ceramics can increase by an order of magnitude. This effect is most pronounced for steel and MgO and less pronounced for aluminum alloy and Al_2O_3 [9–14].

If it assumed that during loading of containers with a powder, the compact gains sufficient strength even behind the incident SW, this should give rise to cracks in the compacted ceramic layer. Indeed, in a coordinate system attached to the detonation front, with passage through the front of an incident (oblique) SW, the velocity vectors of the powder particles are deflected from the initial direction and acquire a component directed to the axis (Fig. 4). It is clear that the velocity vector should somehow change direction again to become parallel to the axis. This rotation of the flow that arose behind the incident SW occurs in a reflected shock wave or compression wave if the flow behind the incident wave is subsonic. When the powder compact is strong enough but low plastic, the flow rotation to the initial direction leads to periodic incipience of through cracks, which divide the ceramics into blocks. The latter are displaced and rotated in the compacted ceramics layer, resulting in deformation of the metal.

In addition to this simplified explanation of the process, we consider the difference in the axial velocity components in the rod and the ceramics flow behind the SW incident front. This difference in the velocity increases, in particular, with increase in the SW intensity or with decrease in the propagation velocity of the sliding loading. It is not difficult to show that with allowance for the rupture of only the velocity components normal to the surface of the front, this difference is equal to the ratio of the jump in pressure (normal stresses) behind the front of an oblique SW to the product of the initial density of the powder and the detonation velocity ($\Delta V = \Delta p/\rho_0 D$).

The presence of the velocity difference and its subsequent equalization should introduce additional stresses into materials and, together with other factors, determine the orientation of the surface of maximum tangential stresses and slopes of through cracks in the ceramics.

The strength of the compact is ultimately determined by the pressures (stresses) behind the SW front in the powder. The latter depend on the initial parameters of the container and the HE layer thickness [1, 7], and, hence, a change in these parameters should lead to a change in the dimensions of steps on the tube and the rod.

The detonation pressure and velocity increase with increase in HE layer thickness. In this case, growth of the specific impulse acting on the tube, which increases the pressures (stresses) behind the SW front, plays a predominant role and should lead to an increase in the strength of the ceramics. An increase in the velocity of the sliding loading can change the incident SW angle and decrease the flow deflection angle, but this should be compensated, at least partially, by an increase in the deflection angle because of the increase in pressure and, hence, in the ceramics density. In this case, kinematic factors play a less significant role, and it is necessary first of all to take into account the growth in stress and strength of the ceramics due to the increase in the SW amplitude. As a result, one might expect an increase in strain in the metal.

As the mass of the tube is decreased, the increase in powder pressure behind the SW front due to accelerated motion of the tube also plays an important role. In this case, the strength of the ceramic compact, the angle of flow deflection behind the incident SW front, and the reverse rotation angle also increase. Ultimately, both factors should lead to an increase in steps on both the rod and the tube, because they increase the ceramics strength and the displacements of the block.

This reasoning refers to results of experiments in which, with the same metal used, the height of steps was higher the thinner the tube and the thicker the HE layer (experiment Nos. 2, 4, 6, 10, and 15), and also to experiments in which tubes of metals with various densities and strength limits were used (experiment Nos. 6–8) or a tube and a rod of various metals were used in one experiment (experiment No. 8), where the depth of traces in duralumin is 2 or 3 times higher than in steel. In particular, use of a less strong copper tube instead of a steel tube, with a slight difference in their densities (experiment Nos. 6 and 7), cannot significantly change the compaction parameters of the ceramics (its strength and flow deflection) and markedly increase the height of steps on the rod and the tube.

Behind the SW incident front, as noted above, there was a difference in the axial velocity components, which, by our estimates, was about several hundreds of meters per second. In the case of a high loading rate, this was apparently responsible for the occurrence of shear strain along the axis in the rod (see Fig. 2b). For the tube, such a difference in the axial velocity components is absent and a shear strain of this direction is not observed.

An increase in the velocity of motion of the load by coating the surface with a thin layer of a high-speed HE changes the specific impulse acting on the tube insignificantly, and, hence, does not influence the strength and density of the ceramics, but decreases both the incident SW angle and the flow deflection angle behind the SW front, and also the angle required for the ceramic flow rotation parallel to the axis. As a result of this, the height of the steps on the tube and the rod should decrease, as was observed in the experiment.

Experiment No. 17 with increased plasticity of the powder indicates that the steps that appeared in the metal cannot be a consequence of the wave formation process in explosive welding but are due to the brittleness of the compacted material.

5. Thus, along with the factors indicated in Sec. 1 there is an additional cause for the origination of cracks in ceramic samples in explosive compaction. It is connected with the features of the flow in the case of sliding loading of a container with a cylindrical layer of powder.

The results of the experiments performed indicate that before the arrival of a rarefaction wave, the strength of the compacted powder immediately behind the SW front can be higher than the strength of steel. This should be taken into account, in particular, in models that describe explosive compaction of powders.

REFERENCES

1. A. I. Matytsin, "Analysis of the process of compaction of a powder in a cylindrical container using a simple model," *Prikl. Mekh. Tekh. Fiz.*, No. 1, 61–70 (1988).
2. R. Prummer, "Dynamic compaction of powders," in: R. F. Davis, H. Palmor III, and R. L. Porter (eds.), *Emergent Process Methods for High Technology Ceramics*, Plenum Press, New York (1984), pp. 621–637.
3. M. A. Meyers and S. L. Wang, "An improved method for shock consolidation of powders," *Acta Metall.*, **36**, No. 4, 925–930 (1988).
4. S. A. Pershin and V. F. Nesterenko, "Localization of shear strain in pulsed compaction of foils of fast-hardening alloys," *Fiz. Goreniya Vzryva*, **24**, No. 6, 120–123 (1988).
5. V. F. Nesterenko and S. A. Pershin, "Strain localization in explosive compaction of fast-hardening metal powders," *Fiz. Goreniya Vzryva*, **23**, No. 5, 159–166 (1987).
6. M. A. Meyers, "Shock-wave consolidation of rapidly solidified metal powders," in: R. Mehrabian and M. Cohen (eds.), *Proc. Fourth Conf. on Rapid Solidification Technology* (Santa Barbara, Dec. 1986), Plenum Press, New York (1987), pp. 451–459.
7. A. I. Lyamkin and A. I. Matytsin, "Mechanical properties of cermet produced by explosive compaction," in: *Dynamics of Continuous Media* (collected scientific papers) [in Russian], Novosibirsk, **62** (1983), pp. 93–101.
8. A. R. Andrievskii and I. I. Spivak, *Strength of Low-Melting Compounds and Materials Based on Them, Handbook* [in Russian], Metallurgiya, Chelyabinsk (1989).
9. S. A. Novikov, "Strength in quasistatic and shock-wave loading," *Fiz. Goreniya Vzryva*, **21**, No. 6, 77–85 (1985).
10. S. A. Novikov, "Shear stresses and spall strength of metals under shock loads," *Prikl. Mekh. Tekh. Fiz.*, No. 3, 109–120 (1981).
11. Z. Rosenberg and Y. Yeshurun, "Determination of the dynamic response of AD-85 alumina within-material," *J. Appl. Phys.*, **58**, No. 8, 3077–3080 (1985).
12. M. Brandes, "Mechanical properties of materials under hydrostatic pressure," in: H. Pugh (ed.), *Mechanical Behaviour of Materials under Pressure*, Elsevier Publ. Comp., Amsterdam–New York (1970).
13. D. Yaziv, Y. Yeshurun, Y. Partom, and Z. Rosenberg, "Shock structure and precursor decay in commercial alumina," in: *Shock Waves in Condensed Matter* 1987, in: S. C. Schmidt and N. C. Holmes (eds.), *Shock Waves in Condensed Matter* 1987, Phys. Sci. Publ., Amsterdam (1988), pp. 297–300.
14. T. S. Duffy and T. J. Ahrens, "Shock and release of polycrystalline magnesium oxide, in: S. C. Schmidt, J. W. Shaner, G. A. Samara, and M. Ross (eds.), *High-Pressure Science and Technology*, AIP Press, New York (1994), pp. 1107–1110.