Conf-940380--2

UCRL-JC-115980
PREPRINT

Structures and Properties of Materials Recovered From High Shock Pressures

William J. Nellis

University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

This paper was prepared for submittal to the proceedings of the
NIRM Symposium on Advanced Materials Institute for Research in
Inorganic Materials
March 14–17, 1994
Tsukuba, Japan

March 1994

Lawrence Livermore National Laboratory

Structures and Properties of Materials Recovered from High Shock Pressures

W. J. Nellis
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550 USA

Abstract

Shock compression produces high dynamic pressures, densities, temperatures, and their quench rates. Because of these extreme conditions, shock compression produces materials with novel crystal structures, microstructures, and physical properties. Using a 6.5-m-long two-stage gun, we perform experiments with specimens up to 10 mm in diameter and 0.001 – 1 mm thick. For example, oriented disks of melt-textured superconducting $YBa_2Cu_3O_7$ were shocked to 7 GPa without macroscopic fracture. Lattice defects are deposited in the crystal, which improve magnetic hysteresis at ~1 kOe. A computer code has been developed to simulate shock compaction of 100 powder particles. Computations will be compared with experiments with 15-20 μm Cu powders. The method is applicable to other powders and dynamic conditions.

Introduction

Shock compression produces dynamic pressures up to the Mbar range, compressions up to a few tens of percents, and temperatures up to a few 1000 K. Dynamic pressure is applied for about a μsec. Strain rates on compression are very high, reaching above 10^8/s. Quench rates on release of pressure are also very high, ranging up to about 10^9 K/s and 10^{12} bar/s. Because of these extreme conditins and rates, shock compression produces material with novel crystal structures, microstructures, and physical properties.

Using a 6.5-m-long two-stage light gas gun with a 20 mm bore, we accelerate projectiles (impactors) up to 4 km/s. When such a projectile impacts a target, pressures from 1–100 GPa (0.01–1 Mbar) are generated, depending on materials and impactor velocity. Impactors typically weigh 5-10 g and so it is straight forward to contain the kinetic energy and momentum of the impactor in a fixture containing the specimen.[1,2] Specimens are typically 10 mm in diameter and 0.001 to 1 mm thick. As an example, 1 μm thick films have been recovered intact from 100 GPa shock pressure.[3] With our 35 mmbore two-stage gas gun larger diameter specimens can be used, although maximum velocities and impact pressures are lower.

In this paper we give two examples. The first example shows that a disk of a brittle ceramic oxide can be shocked to relatively high pressures without macroscopic fracture, that is, without breaking the oxide disk. The high strain rates induce shock defects, which change the properties. In this case, the disk is a high-temperature superconductor and the physical property is the magnetic hysteresis ΔM induced in the disk by an applied magnetic field. The second example is the combination of the development of a computer code to simulate the dynamic compaction of 100 individual powder particles and the comparison of the computations with the results of gas-gun experiments using Cu powders as a simple test material.

$YBa_2Cu_3O_{7-x}$ Disks Shocked to 6.6 GPa

Bearings made from new high-transition-temperature (high-T_c) superconducting oxides are a possible application of these new superconductors. External magnetic fields are generated in such bearings by superconducting magnetic fluxoids which should be strongly pinned in the lattice to prevent dissipative losses. The purpose of a superconducting bearing is not to transport high currents and thus the problem of relatively small intergranular critical current density in polycrystalline oxide superconductors is minimized. However, intragranular critical current density needs to be increased by increasing the number and strength of flux-pinning sites within the lattice. In so doing, the magnetic field which can be generated and sustained by a bearing material is increased. High densities of lattice defects are induced in shock-compacted powders of $YBa_2Cu_3O_7$ and the dislocations and stacking faults generated are effective in increasing flux-pinning energies and intragranular critical current densities.[4] However, an effective technique is needed to shock-induce lattice defects and ΔM in high-T_c oxides, which does not fracture the specimen. These defects should enhance flux-pinning energies and intragranular critical current densities.

An attractive material to investigate is $YBa_2Cu_3O_7$. An ideal form of $YBa_2Cu_3O_7$ to investigate is melt-textured material because it consists of large disk-shaped grains several mm across and several 10 μm thick, in which the c axis of the orthorhombic crystal structure is along the thin direction of each disk-shaped grain. Superconducting fluxoids point preferentially along the c axis, and these grains are preferentially aligned in melt-textured $YBa_2Cu_3O_7$.

Our objective is to shock-induce lattice defects in a crystallographicaly aligned disk without fracture, at least on a macroscopic scale. In this way, an oriented shocked specimen can be annealed and its superconducting properties measured in a straight forward manner. The slip planes in $YBa_2Cu_3O_7$ are in the basal plane of the orthorhombic crystal structure.[5] Thus, shocking $YBa_2Cu_3O_7$ powders causes increasing fracture with increasing pressure,[6] because the slip planes are randomly oriented. Shocking a disk-shaped single crystal along the c axis normal to the plane of the specimen is expected to fracture it into many small pieces, since no slip direction is available along the shock direction. On the other hand, a small $YBa_2Cu_3O_7$ single crystal shocked at 45° from the basal plane broke into only a few pieces which were heavily defected.[7] Thus, controlling the crystallographic orientation of a specimen with respect to the shock direction is an effective way to control fracture while shock-inducing defects.

For this reason, a dense melt-textured $YBa_2Cu_3O_7$ specimen disk 7.7 mm in diameter and 1.1 mm thick was embedded in a steel recovery capsule, which in turn was embedded in a steel fixture, and shocked to 6.6 GPa at an angle of 30° with respect to the average c-axis direction of $YBa_2Cu_3O_7$. The velocity of the lexan projectile was chosen to give the desired impact pressure in steel. The experiment is illustrated in Fig. 1; in this configuration the direction of shock propagation is about 30° from the average c-axis direction of the disk-shaped melt-textured $YBa_2Cu_3O_7$.

The shock pressure in the oriented melt-textured $YBa_2Cu_3O_7$ disk produced a one-piece specimen. The specimen was easily handled without breaking for post-shock annealing and SQUID magnetometer measurements. The shock pressure did not change the superconducting transition temperature of 92 K.

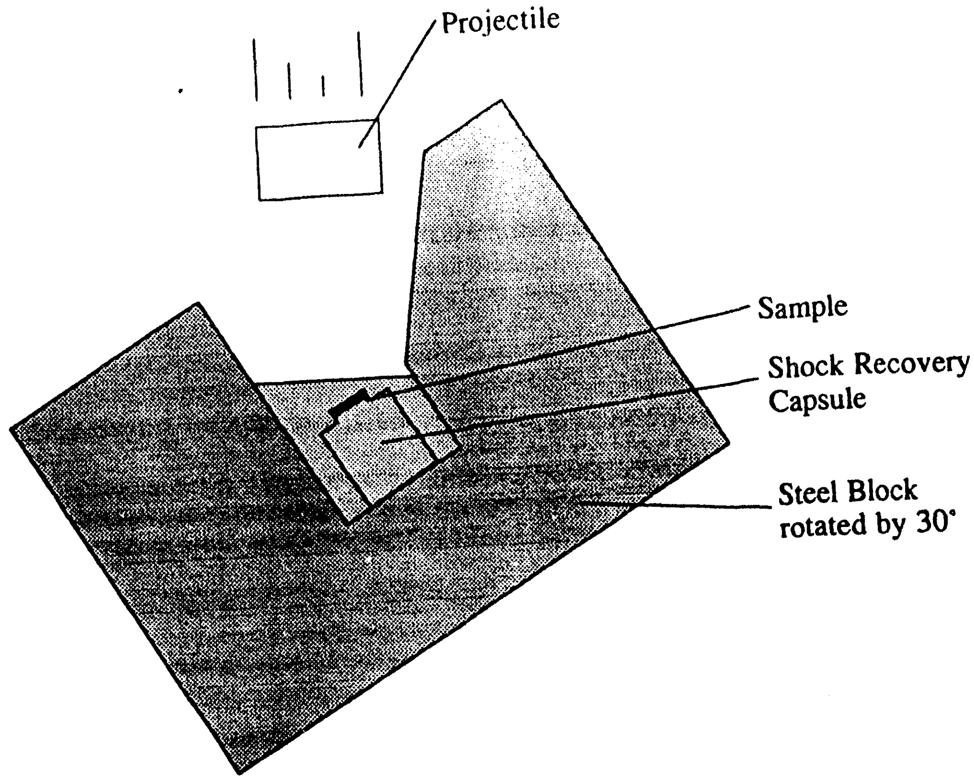

Figure 1. Schematic of fixture to shock a disk-shaped specimen of melt-textured $YBa_2Cu_3O_7$ without macroscopic fracture.

Magnetic moment induced in the specimen was measured at 70 K as a function of applied magnetic field up to 40 kOe. Magnetic hysteresis ΔM is the difference in magnetic moment M induced on increasing and decreasing applied magnetic field H. Magnetic hysteresis is sensitive to shock-induced changes in microstructure and, thus, to changes in critical current density. At an applied magnetic field of 1 kOe, annealing the specimen in oxygen was found to increase the magnetic hysteresis of the specimen relative to the initial state. Thus, the ability of the shocked and annealed specimen to act as a magnetic-bearing material is enhanced.

Magnetic hysteresis ΔM versus applied magnetic field was measured initially, after shocking, and after successive heat treatments in oxygen at 890° C for various times, followed by 4 hours in oxygen at 450°. The results for an applied field of 1 kOe are plotted in Fig. 2 as ΔM versus cumulative annealing time at 890° C. The dashed baseline in Fig. 3 is the reference result for the unshocked specimen. At zero annealing time the lower ΔM point is for the as-shocked specimen; the upper ΔM point near zero corresponds to 10 minutes at 890° C. After a cumulative annealing time of 15 hours, ΔM is enhanced over the starting value. An ehancement of about 15% is observed after a cumulative annealing time of 48 hours.

These results show that the brittle oxide $YBa_2Cu_3O_7$ can be shocked to 6.6 GPa without macroscopic fracture, provided the disk-shaped specimen is in the preferentially oriented melt-textured form and is shock-compressed at an angle of about 30° from the effective c axis of the orthorhombic-phase specimen. Subsequent anneals in oxygen at

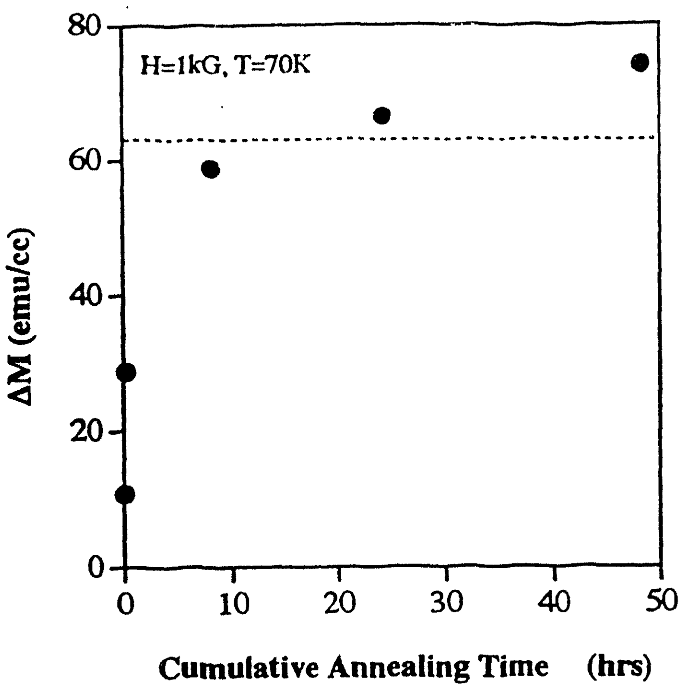

Figure 2. Magnetic hysteresis DM at 1 kOe and 70 K versus cumulative annealing time at 890° C in oxygen for the specimen shocked to 6.6 GPa. The lower DM point at zero annealing time is for the as-shocked specimen; the upper DM point near zero time corresponds to 10 minutes at 890° C.

890° C produce a magnetic hysteresis which is enhanced relative to the initial unshocked state, as expected for shock-induced dislocations and stacking faults.[4] This work is described in more detail elsewhere.[8]

Dynamic Compaction of Powders

The dynamic compaction of powders is a technique to produce a wide variety of dense ceramic, metallic, and other specimens with potentially novel properties.[9-13] The method, for example, is attractive to consolidate nanocrystalline powders without grain growth. In this method consolidation is achieved by dynamic high pressures which densify powders and last for very brief times of ~1 μs. The fast time scale offers the opportunity to consolidate fine-grained powders, which do not have time to increase their grain size. The fast time scale also produces heterogeneous surface heating on particle boundaries, high quench rates and possible interfacial bonding between particles. Several phenomenological models have been developed to describe the process.[9-11] However, a generalized computational simulation is needed which can test various ideas and guide experiments to produce dense compacts. In this way, a wide variety of issues could be addressed computationally, including heterogeneous pressures, temperatures, and and their quench rates for various particle-size distributions, plastic flow, fracture, and phase transitions.

For this reason we initiated development of a computer simulation of the compaction of powders to iterate with experimental results. This computational model was developed in collaboration with Dr. David Benson. Copper was chosen as a test material because i)

Cu is a relatively simple material with an available material model at high shock pressures,[13] ii) real-time shock compression data are available for porous Cu for comparison with computation,[14] and iii) Cu powders are readily available for experiments to compare observed changes in particle shape with computational predictions.

In this model about 100 powder particles of a given size distribution and average initial porous density fill a box using a Monte Carlo method and the particles are compressed dynamically using an Eulerian computer code. The equation of state and constitutive model of each solid particle, initially at normal density, are those of Cu. The initial computations were performed in two dimensions, which require less computer time than three dimensions. The initial size of the box containg the particles is 160 μm with 100 Eulerian zones on a side. The particle sizes were chosen as in the experiment described below. The consolidation was calculated for a compressive wall velocity of 0.2 km/s or about 2 GPa shock pressure in Cu powder of density 6.1 g/ cm^3.

In order to test the computational predictions, spherical Cu powders 15-20 μm in diameter were dynamically compacted using a 6.5-m-long two-stage light-gas gun. The powder specimens were 10 mm in diameter and 0.5 mm thick and were placed in a steel capsule. For comparison of experiment with calculation, we use the fact that most of the internal energy and consolidation are achieved in the powder in the first shock wave. The computed single-shock compaction is, thus, compared with results from experiments in which compaction is achieved by a reverberating shock wave in the 0.5 mm thick specimen. Measured initial powder density was 6.1 g/cm^3. Shock compression data for porous Cu[14] and the standard shock-impedance-match method were used to estimate the impact velocity of the lexan plastic projectile required to obtain the wall velocity used in the computation. The photomicrograph result for a wall velocity of 0.2 km/s, a lexan impact velocity of 1.1 km/s, and a first shock wave in the powder of 2 GPa is in good agreement with the computation.[15, 16]

In summary the computational results for Cu powders are in good agreement with experimental observations of the shapes of particles consolidated at pressures up to a few GPa,which shows that the simulation is accurate up to a few GPa. The computational method could be generalized to other materials, size distributions, compaction rates, and higher pressures.

Acknowledgments

This work was performed by LLNL under the auspices of the US DOE under contract W-7405-ENG-48. We acknowledge N. A Hinsey for performing the gas gun experiments. This work was supported by H Division and the LLNL Institute of Geophysics and Planetary Physics.

References

1. J. J. Neumeier, W. J. Nellis, M. B. Maple, M. S. Torikachvili, K. N. Yang, J. M. Ferreira, L. T. Summers, J. I. Miller and B. C. Sales, High Pressure Res. 1, 267 (1989).

2. A. J. Gratz, W. J. Nellis, J. M. Christie, W. Brocious, J. Swegle and P. Cordier, Phys. Chem. Minerals 19, 267 (1992).

3. R. Koch, W. J. Nellis, J. W. Hunter, H. Davidson and T. H. Geballe, Pract. Met. 27, 391 (1990).

4. S. T. Weir, W. J. Nellis, M. J. Kramer, C. L. Seaman, E. A. Early and M. B. Maple, Appl. Phys. Lett. 56, 2042 (1990).

5. M. J. Kramer, L. S. Chumbley and R. W. McCallum, J. Mat. Sci. 25, 1978 (1990).

6. W. J. Nellis, C. L. Seaman, M. B. Maple, E. A. Early, J. B. Holt, M. Kamegai, G. S. Smith, D. G. Hinks and B. Dabrowski, High Temperature Superconducting Compounds: Processing and Related Properties, Warrendale, PA: TMS Publications, 1989, pp. 249-264.

7. S. T. Weir, W. J. Nellis, C. L. Seaman, E. A. Early, M. B. Maple, M. J. Kramer, Y. Syono, M. Kikuchi, P. C. McCandless and W. F. Brocious, Shock-Wave and High-Strain-Rate Phenomena in Materials, New York: Dekker Press,1992, pp.795-808.

8. W. J. Nellis, S. T. Weir, N. A. Hinsey, U. Balachandran, M. J. Kramer and R. Raman, to be published in the proceedings of the AIRAPT/APS High Pressure conference, June 28-July 2, 1993, Colorado Springs.

9. C. F. Cline and R. W. Hopper, Scripta Met. 11, 1137 (1977).

10. W. H. G ırdin, J. Appl. Phys. 55, 172 (1984).

11. V. F. Nesterenko and A. V. Muzykantov, Sov. Combust. Explos. and Shock Waves 21, 730 (1985).

12. E. K. Beauchamp, M. J. Carr and R. A. Graham, J. Am. Ceram. Soc. 68, 696 (1985).

13. D. J. Steinberg and M. W. Guinan, J. Appl. Phys. 51, 1498, (1981).

14. LASL Shock Hugoniot Data, edited by S. P. Marsh, University of California Press, Berkeley, 1980.

15. D. J. Benson and W. J. Nellis, submitted, 1993.

16. D. J. Benson, Comp. Meth. Appl. Mech. Eng. 99, 235 (1992).

DATE
FILMED
5/18/94

END