Electrical resistivity of silver foils under uniaxial shock-wave compression

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The electrical resistivity of silver foils 15–25 μm thick was measured during shock-wave compression between sapphire anvils in the pressure range 25–120 kbar. Comparison of isothermal resistivity vs compression from shock measurement to a simple semiempirical calculation of resistivity under hydrostatic compression shows shock data to be consistently higher than hydrostatic results. Shock results depend on purity and thermal history of the silver foils. Deviation between shock and hydrostatic results is attributed to resistivity of vacant lattice sites generated by high-strain-rate plastic deformation in uniaxial shock compression. Estimated vacancy concentrations at 100 kbar are $(1–2)\times10^{-3}$ per lattice site and concentrations vary approximately as the three-halves power of total strain. The high vacancy concentrations may be evidence for dislocation speeds near shear-wave speed. Annealing and microscopy studies of foils recovered after shocking give additional support to the above conclusions.

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I. INTRODUCTION

Measurements of electrical resistance of crystalline materials as a function of pressure can tell us something about properties of ideal lattices and lattice imperfections. This is possible because changes in the ideal lattice can affect resistivity by changing the electron band structure and electron coupling with the lattice vibration spectrum; rudimentary theory exists for comparison with experimental results.[1,2] In addition, changes in number and types of imperfections will affect electron scattering and, hence, resistivity.

Resistance changes in metals due to transient high pressure generated by shock waves have been measured,[3] but there has been no systematic attempt to compare these results with static high-pressure results or theory so that properties of lattice defects under dynamic pressure might be studied. Evidence for shock-induced defect generation is found in a number of metallurgical and annealing studies on metals which were shocked for a short duration and relieved to atmospheric pressure.[4–6] While many defects generated by the shock wave will have annihilated or migrated to sinks before examination, these studies indicate some of the effects which different shock strengths and initial conditions have on the point and line imperfection densities and configurations generated.

Shock-induced resistance changes have been measured for copper, iron, nickel, and ytterbium, as well as manganin alloy.[3,7] Fractional resistance change for a given pressure level is generally greater for shock compression than for hydrostatic compression, though agreement among different shock experimenters has not been good. Material history might be responsible for these discrepancies; unfortunately, few attempts have been made to do experiments on well-characterized material. Good experiments require a well-characterized initial condition of the metal as well as good shock-impedance match between metal and anvil, geometry that assures uniaxial compression, and elimination of perturbations by electrical leads. In addition, careful analysis is necessary to account for thermal effects occurring in shock compression so that comparison can be made with hydrostatic experiments and theories.

In the experiments described in this paper, electrical resistance changes in silver foils were monitored during uniaxial compression by shock waves; foils were 15—25 μm thick. Electrical resistance of silver under hydrostatic compression was previously measured by Bridgman,[2] but no previous studies on silver resistance under shock compression have been published. Dynamic stress levels ranged from 25 to 120 kbar and were generated by high-velocity impact; shock duration was 0.5 μsec. The voltage drop across the foil due to 150 A of current was monitored during this time. In several cases, foil fragments were recovered after the experiment and examined by microscopy and isothermal annealing.

The present work also involved several types of analysis. Using a Debye model of a solid, a method was developed for computing isothermal resistivity as a function of volume. When a single parameter is adjusted to experimental results, the computation agrees closely with the experiments of Bridgman to 30 kbar. This method was also used to correct shock resistivity data to isothermal conditions. Deviations between isothermal data from uniaxial shock compression and calculated hydrostatic results are attributed to resistivity of lattice imperfections generated by plastic deformation in the shock wave.

The purpose of this paper is to present experimental results on shock resistivity of silver foils, to put the isothermal analysis on a firm footing, to consider all possible effects on the resistivity, and to establish credibility of shock-generated defect concentrations deduced.

Presentation will begin with a description of experimental design and procedure followed by analyses needed to reduce acquired data to meaningful forms, results of the experiments and data reduction, and finally a statement of conclusions.

In summary, by careful experimental design and sample preparation, accurate reproducible resistance measurements during shock compression were accomplished. Shock resistivity depends significantly on specimen purity; some dependence on thermal history may also be indicated. An approximate semiempirical

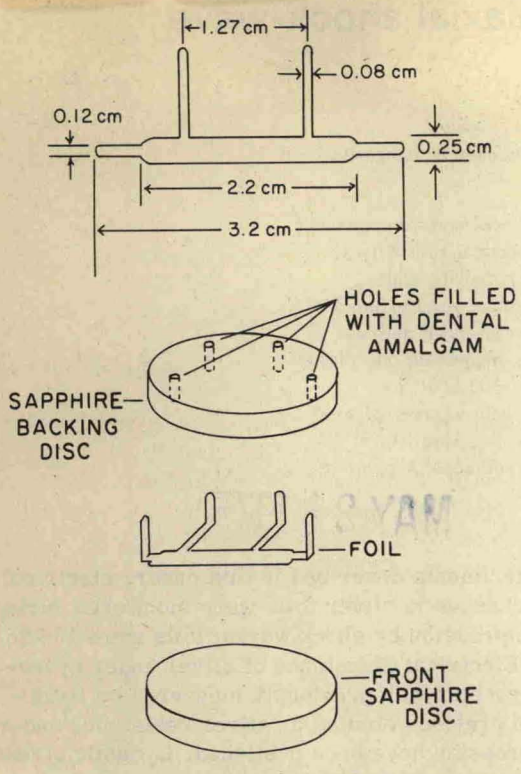

FIG. 1. Details of foil-anvil sandwich. (a) Foil dimensions. (b) Sandwich, exploded view.

resistivity computation allows comparison of hydrostatic and shock isothermal resistivities for silver. Shock results are significantly higher and the deviation is attributed to resistivity of vacant lattice sites generated by plastic deformation in uniaxial shock compression; estimates of vacancy concentrations in shock-deformed silver are given. The results and interpretation are consistent with earlier shock experiments. Postshock examination of foils gives evidence for plastic deformation by slip and an estimate of final vacancy concentration.

II. EXPERIMENTAL PLAN AND PROCEDURE

In terms of a basic study of resistivity of metal under pressure, one wishes to choose a metal which typifies metallic behavior, and in as many ways as possible behaves according to simple theories. Silver was chosen since it is available in high purity, is resistant to oxidation, has no known pressure-induced phase transitions, behaves at least qualitatively according to predictions of a simple model for the pressure effect on resistivity, has a Debye temperature well below room temperature, simplifying many calculations, and has a shock impedance close to that of a readily available anvil material (Al_2O_3).

To obtain sizeable voltage drops it is necessary to use thin metal foils and high electric currents. Furthermore, for experiments to be characterized by one-dimensional compression, the specimen should be about 100 times wider than it is thick. Typical sample dimensions are shown in Fig. 1. Sample resistance at room temperature was about 5 mΩ; current was about 150 A.

High pressures for the experiments were generated by high-velocity impact. To avoid inductive coupling effects it was necessary to use nonconducting impactors. Figure 2 represents schematically the experimental configuration. Details of the projectile launching facility have been published previously.[8]

A. Specimen preparation and characterization

Specimen preparation was a multistep process involving mechanical polishing, cutting to desired shape, thickness measurement, microscope examination, annealing, resistance ratio measurements, and target assembly.

Cold-rolled silver foils were obtained from the Materials Research Corporation (MRC) and the Wilkinson Company (W3N). Mean grain size was about 75 μm in MRC foils and about 35 μm in W3N foils. There was some preferred orientation of grains due to the cold rolling. Possible influences these and other experimental details might have on results are discussed in Appendix C.

To give a uniform surface finish the foils were mechanically polished with alumina abrasive on a wheel. Foils were held flat and rigid during polishing by bonding them to quartz glass plates with phenyl salicylate. Next, specimens of desired shape were photoetched from the polished foils; a positive-working photoresist[9] and a ferric nitrate photoetch solution were used. Foil thicknesses were measured mechanically using gauge blocks and an electronic dial depth gauge; thickness variation on a foil was about ±4%. Microscope examination at 100× magnification showed faint scratches from polishing, some tarnish and occasional pits from the photoetch process, but over-all the foil surfaces were smooth and relatively stain free.

Cut foils were annealed at 800 ± 15 °K for 1—2 h in a 10^{-5}—10^{-6} Torr vacuum. Cooling took place at less than 100 °K/h.

To characterize purity and state of anneal of each foil used, specimen resistance was measured at 4.2 °K and room temperature using 2 A of current and measuring the potential drop with a Keithley 148 nanovoltmeter. Foil leads were clamped between copper blocks; current reversal was used to nullify thermal emf's. Results are shown in Table I. Spectrographic analyses were consistent with relative purity of W3N and MRC foil measured by resistance ratios; these analyses also indicated that foil surfaces were probably contaminated by Al_2O_3 particles acquired during polishing.

B. Target assembly

Target assembly involved bonding the silver specimen between sapphire anvil plates, potting the sandwich in a target holding ring, attaching electrical coaxial cables, and providing electrical shielding for the sample. Synthetic sapphire (single-crystal Al_2O_3) disks 3.8 cm in diameter and 0.3 cm thick were purchased from the Adolph Mellor Company, which specified the perpendiculars to the disk faces as oriented 50°—90° from the *c* axis of the single crystals. Sapphire is hexagonal structure so that one might expect that shock-wave propaga-