

APPENDIX A: SHOCK REVERBERATION ANALYSIS

The reverberation shock (P_x, u) states are found by the method of characteristics in the (P_x, u) plane. Quadratic fits, $P_x = A_i u + B_i u^2$, to the principal pressure-particle velocity curves are used in the numerical solution. (The principal Hugoniot curve through $P_x = 0, u = 0$ was used to generate all characteristics.) For silver, $A_1 = 3.3384$ and $B_1 = 17.448$, and for sapphire, $A_2 = 4.44$ and $B_2 = 1.36$ (P_x is in Mbar and u in cm/ μ sec). States in the (P_x, u) and (t, x) planes are sketched in Fig. 11.

Solution of the simultaneous equations representing the curve intersections in the (P_x, u) plane for even numbered states is different from the solution for the odd numbered states. For the n th even numbered state the quadratic equation to be solved, $au^2 + bu + c = 0$, has coefficients

$$\begin{aligned} a &= B_1 - B_2, \\ b &= A_1 + A_2 - 2B_1(u_{n-1} - u_R) + 2B_2u_p, \\ c &= -A_1(u_{n-1} - u_R) + B_1(u_{n-1} - u_R)^2 - A_2u_p - B_2u_p^2, \end{aligned}$$

and the positive branch of the quadratic solution is used. Here u_p is twice the particle speed of the final state and u_R is the solution of $B_1u_R^2 + A_1u_R - P_{n-1} = 0$. For the odd numbered states,

$$\begin{aligned} a &= B_1 - B_2, \\ b &= -A_1 - A_2 - 2B_1(u_{n-1} + u_R), \\ c &= A_1(u_{n-1} + u_R) + B_1(u_{n-1} + u_R)^2, \end{aligned}$$

and the negative branch is used.

To find volume and temperature of a reverberation state, consider a shock from an arbitrary known initial state ($P_{n-1}, V_{n-1}, T_{n-1}$) to a final state (P_n, V_n, T_n). The Rankine-Hugoniot relation is

$$E_n = E_{n-1} + \frac{1}{2}V_0(P_n + P_{n-1})(X_{n-1} - X_n),$$

where $X = V/V_0$ and E is internal energy. Also

$$E_n = E_p(X_n) + \frac{3R}{M}T_n \left(1 + \frac{1}{20} \frac{\theta_n^2}{T_n^2}\right)$$

from the equation of state (Sec. III. B), where E_p is the internal potential energy, R is the gas constant, and M is molecular weight. Hence, E_n can be eliminated between the equations and the equation for T_n becomes

$$\begin{aligned} T_n^2 - (M/3R)[E_{n-1} + \frac{1}{2}V_0(P_n + P_{n-1})(X_{n-1} - X_n) \\ - E_p(X_n)]T_n + \frac{1}{20}\theta_n^2 = 0. \end{aligned}$$

Now all (P_n, V_n, T_n) reverberation states can be calculated if u_p and T_0 are given.

APPENDIX B: ADDITIONAL THERMAL EFFECTS

A. Heat flow calculation and discussion

There may be significant heat flow into the silver foil from the epoxy bonding layer during the impact experiment. Such heat flow could affect silver resistance data. Epoxy, being very compressible, gets much hotter than silver when shocked. The single-shock temperature rise at 120 kbar in epoxy is about 800 °C⁶³,

silver temperature rises about 90 °C and sapphire temperature about 10 °C. In these experiments, where the shocked state is reached by wave reverberations, the epoxy temperature rise is approximately 370 °C at 120 kbar.

The one-dimensional heat flow equation was solved for three slabs, epoxy-silver-epoxy. Details of the solution and computational method are given in Ref. 64. The solution does indicate significant heat flow into the silver from the epoxy in 0.5 μ sec. The sandwich reaches thermal equilibrium in about 10⁻⁴ sec.

Accurate estimates of the temperature rise are not possible because of incomplete knowledge of epoxy thickness and of variation of the thermal conductivity of epoxy with increasing pressure and temperature. Values for these two epoxy parameters are decisive in determining the temperature rise due to heat flow in silver. Thermal conductivity of epoxy increases monotonically with pressure to 25 kbar.⁶⁵ Similarly, thermal conductivities of most dielectrics increase with temperature, but melting or decomposition might change this behavior.

Micrometer measurements of sandwich thickness indicated a total epoxy thickness of $-0.5 \pm 2.5 \mu\text{m}$, the uncertainty being indicative of micrometer accuracy. This indicates a typical epoxy layer of less than 1.2 μm average thickness; perhaps about 0.6 μm is typical. One would not expect a thinner layer since the silver foil thickness measurements indicated a thickness nonuniformity of about $\pm 0.6 \mu\text{m}$.

Estimated results for the temperature rise and resistivity change in silver due to heat flow $\frac{1}{2} \mu\text{sec}$ after shock arrival are given in Ref. 64. These estimated resistivity changes can account for some of the resistivity deviation between shock and hydrostatic results: as much as 22% in MRC silver and 9% in W3N silver. Correcting point-defect resistivity accordingly would reduce calculated magnitudes for total vacancy concentrations but would increase the computed concentration difference between MRC and W3N silver.

An experimental indication of heat flow effect may be present in shot 73-047 at 94 kbar. The W3N foil was thinned down to 17.6 μm from the 24.4- μm thickness of the other W3N foils; the isothermal resistivity data point without heat flow correction is indeed slightly high (Fig. 8). Heat flow correction according to Ref. 64 would bring the data point in line with the other W3N points. However, stress relaxation effects could also account for the position of that data point (Sec. IV G).

It should be noted that, in addition to other uncertainties in the calculation, the differential equation used may not completely describe the physical situation. The differential equation is a diffusion equation and neglects thermal waves which may be generated by the steep temperature gradients.⁶⁶

B. Temperature rise due to plastic deformation and porosity

Plastic deformation is an irreversible process; the associated entropy rise increases thermal energy.⁶⁷

Calculation shows that temperature rise in silver due to work of plastic deformation is of marginal significance for the present work; at 110 kbar the temperature rise is 2.0 °K for a maximum resolved shear stress of 0.25 kbar.⁴⁷ Since actual magnitude of resolved shear stress in silver foils in the present experiments is uncertain, the correction for this temperature rise was not applied to the data.

As little porosity as 0.1% voids would significantly affect temperature rise due to shock compression. However, transmission electron microscopy of cold-rolled metal foils shows no evidence of voids.⁶¹

APPENDIX C: DETAILS OF SPECIMEN CONDITION

Aside from the specimen characterization in terms of purity and anneal, there are a number of other aspects of the foil state prior to the impact experiment which should be discussed. Variations in the aspects discussed here are not believed to have significantly influenced experimental results.

A. Effects of foil thickness variation on results

Average thickness of MRC foils was 16.2 μm while for all except one of the W3N foils the average thickness was 24.4 μm . In order to check if the observed differences in experimental results between MRC and W3N-type silver were due to the differences in foil thickness, a W3N foil was thinned down to 17.6 μm . This shot, 73-047, gave resistivity results consistent with the other thicker W3N foils. We conclude that the observed difference between the two foil types is not due to different thickness.

B. Effect of specimen handling on state of anneal

Most of the experiments were done on annealed foils. The state of anneal was checked by measuring resistance at 4.2 °K. The question arises whether the state of anneal was preserved during the handling involved in target assembly. Tests were made on annealed MRC foils. To simulate assembly they were subjected to screw pressure between two glass plates wetted with acetone. One foil was also accidentally bent during this handling. Resistance at 4.2 °K was the same before and after handling within the 1% accuracy of measurement. We conclude that the state of anneal was not significantly affected by this handling.

Spot-welding silver wires to the foil tabs and soldering the wires to coaxial cables after the foil was mounted in the target did cause some transient heating but probably did not alter significantly the state of anneal of the specimens.

C. Condition of foil surfaces

Generation of dislocations at sources on the specimen surface has been shown to be important in quasistatic deformation of silver single crystals.⁶⁸ This raises the question whether differences in surface condition could explain the differences in shock resistivity in the two silver foil types studied here. The surface state was rough and poorly defined from metallurgical and sur-

face physics viewpoints [Fig. 10(a)]. Both foil types were prepared in nearly identical fashion except that the MRC foil, as received, had more initial surface roughness and, therefore, was mechanically polished for a longer time. Since no significant effect of surface preparation was found in the lithium fluoride precursor decay studies,⁵⁰ surface structure differences are not believed to be the cause of observed resistivity difference between foil types in the present work.

Surfaces with less roughness and less deformation could probably have been achieved using cerium oxide as the final polishing abrasive instead of the 0.05- μm alumina employed in this work. A nonmechanical polishing technique for mirror finishes developed by Henry, Hockey, and Mitchell⁶⁹ might also have improved the surface condition.

D. Grain size and preferred orientation

The mean grain sizes in the two types of silver foil used were significantly different. For annealed W3N foil, the mean grain size was about 35 μm , while for MRC foil, annealed and unannealed, it was about twice that. In both cases the mean grain size seen on the foil surface was greater than the foil thickness; we then expect that a traverse of the foil thickness is usually confined to a single grain. For this reason, the difference in grain size is not expected to have a significant effect on defect production, dislocation glide, and dislocation generation. One can envision some effect on dislocations moving on glide planes at large angles to the shock direction; such dislocations might reach and interact with grain boundaries.

It should be noted that there is some effect of grain size on yield stress at low strain rates.⁷⁰ A factor-of-2 increase in grain size in silver causes an 8% decrease in yield stress. However, in shock experiments no effect of grain size on HEL after 19 mm of shock propagation was noted in Armco iron.⁷¹ An effect of grain size on precursor attenuation in the first mm or less of shock propagation cannot be ruled out. Lithium fluoride work showed no effect of the number of subgrain boundaries on the precursor decay or HEL,⁵⁰ whereas in copper there was an effect.⁵⁷ Grain size is thus a possible, but not likely, source of the difference in defect resistivity between the two foil types.

This is an appropriate time to discuss preferred orientation of crystallites in cold-rolled foils. The topic has been reviewed by Barrett and Massalski.⁷² For silver rolled at room temperature or below the texture is described by the (110) plane parallel to the rolling plane and the $[\bar{1}\bar{1}2]$ direction parallel to the rolling direction. Other crystallite orientations are present but with less frequency.

Rolling texture changes to a new texture on low-temperature annealing but becomes random with annealing above 800 °C. After long annealing at 433 to 533 °C (anneals in present work were 1–2 h at 535 °C the orientation is the same as the original rolling texture.

Based on the above discussion, it is most likely that