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PROPERTIES OF HOT EXPANDED LIQUID ALUMINUM*

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Measurements of temperature, volume, enthalpy, and electrical resistivity have been made on aluminum expanded isobarically by 50% in volume to temperatures of about 4000 K. These measurements are compared with the predictions of liquid-metal pseudopotential theory.

1. BACKGROUND

In the isobaric expansion experiment (IEX)¹, cylindrical wire samples approximately 1 mm in diameter are rapidly heated by the discharge of a capacitor bank through them in a time of 12-50 μ s. The sample is subjected to a predetermined ambient pressure of a few tenths of gigapascals by argon gas in a pressure cell. The volume of the cell is large enough so that changes in pressure produced by gas displacement from sample expansion are negligible. In addition, the rate of expansion is slow enough to allow sound waves to communicate pressure changes throughout the cell in a time interval that is short compared with the measurement times of the experiment. As a result, the pressure in the cell is relatively constant and uniform. The compressibility of the metal samples is sufficiently small that the results are not sensitive to the cell pressure. The most important purpose of the high pressure gas is to allow large expansion of the metal without large distortions in sample geometry. The density of argon gas increases rapidly with pressure, and is 1.28 g/cm³ at a pressure of 0.24 GPa. Taylor instability at the metal surface is thus substantially reduced. In addition the amount of expansion before the boiling line of the metal is reached is increased. The inert gas also prevents chemical interaction with the hot surface.

Optical diagnostics are performed through sapphire windows as shown in Fig. 1. In one line of sight (LOS) continuous back lighting is provided by a CW argon-ion laser. The shadow of the sample is directed to a slit oriented perpendicular to the wire sample axis, and an electronic streak camera is used to record shadow width at the slit as a function of time. If the sample is

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FIGURE 1

Schematic representation of optical diagnostics for the isobaric expansion experiment.

clamped at each end to prevent axial motion then the specific volume of the sample varies as the square of the shadow width. The streak is started shortly before the sample expansion begins in order to calibrate the magnification of the system.

A second LOS is used to determine the degree of sample distortion in the measurement. A Q-switched ruby laser is used as a back lighting source to take an overall snapshot picture of the sample at a late time. Shots which show significant distortion are discarded. A fast three channel optical pyrometer is used to determine the surface temperature of the sample as a function of time.

The sample heating current is measured using a wide band current transformer. Voltage probes are arranged to contact the sample surface at a known distance of separation and the voltage difference between probes is recorded. Inductive voltage corrections are determined by differentiating the recorded current pulse and using a sample self inductance that results in a resistive voltage which increases smoothly from zero at the start of the pulse.

The integral of the product of current and resistive voltage gives the enthalpy input to the sample. Since all variables are measured simultaneously, time can be eliminated as a common parameter. The enthalpy is determined

continuously as a function of temperature, giving specific heat data. Since current, sample diameter and resistive voltage are measured, one can determine the electrical resistivity, properly corrected for thermal expansion, as a function of either specific volume, enthalpy or temperature. Since the pressure is known, the volume data can be combined with either the enthalpy or the temperature to produce an isobar of the equation of state.

2. MEASUREMENTS

IEX measurements have been made on aluminum. Since it is such a good conductor a sample diameter of 0.69 mm was chosen in order to reach melting in the desired time with the available capacitor bank. Sudden rapid acceleration in sample growth rate with a corresponding rapid rise in apparent electrical resistivity was observed, and determined the upper bounds of the data. Figure 2 shows the pressure-volume plane with the track of these measurements, made at a pressure of 0.3 GPa. The dotted curve ends at the onset of the sudden

FIGURE 2

Pressure vs volume plane for aluminum. The critical points and boiling curves of Young and Alder and of Kolgatin and Khachatur'yants are shown along with the melting transition. The IEX track ends at the onset of sudden rapid growth in sample diameter and resistivity.

rapid growth. Young and Alder² used a hard sphere van der Waals model to predict a critical pressure of 0.546 GPa and a critical volume of $3.91 \times 10^{-5} \text{ m}^3 \text{ mol}^{-1}$ corresponding to $v_c/v_0 = 3.93$ where v_0 is the specific volume at room temperature and atmospheric pressure. Their boiling line is shown in the figure. Kolgatin and Khachatur'yants³ made a fit to the critical data in the review by Fortov, et al⁴ and other standard thermophysical data to give an interpolation equation of state. Their boiling line is also shown. It appears unlikely that the instability is caused by the onset of boiling. The behavior is rather like that described by Lebedev⁵ and the current densities of these measurements are in the range he discusses.

The relatively low mass density of the metal also contributed noticeably to hydromagnetic instability. The magnetic pressure evidently caused axial movement of metal producing a bulge at the tip of one sample clamping jaw. As a result the full radial expansion was not achieved and the volumes are quite substantially less than those expected from the literature. The electrical resistivities near the beginning of the liquid range where this problem was not significant are in good agreement with the literature. The pyrometer measurements gave results in excellent agreement with extrapolation of the 1973 Hultgren⁶ tables, and extend the data to 4000 K. The full details of the measurements will appear in *Int. J. of Thermophysics*, along with data for copper.

3. DISCUSSION

Aluminum is considered to be a simple, nearly free electron metal which provides a useful test for theory. The thermophysical properties of liquid aluminum near normal density have been calculated using liquid metal pseudopotential theory.⁷ In the present calculations we used a Harrison pseudopotential⁸ with a modified Geldart-Vosko dielectric constant,^{9,10} and a set of parameters fitted to reproduce the solid isotherm and the Grüneisen parameter. The thermodynamic properties were calculated by minimizing the Helmholtz free energy with respect to the hard sphere packing fraction and taking the appropriate derivatives of the free energy to obtain pressure and energy. In these calculations we used a soft sphere rather than a hard sphere reference entropy.¹¹

The resistivity was calculated by the method of Ashcroft and Lekner.¹² The predicted expansions (Fig. 3) and electrical resistivities (Fig. 4) are in reasonably good agreement with the measurements. These results suggest that liquid metal pseudopotentials may be useful for metals expanded to 50% of their solid density.

FIGURE 3
Thermal expansion of aluminum. The error bars correspond to $\pm 6\%$.

FIGURE 4

Electrical resistivity of aluminum. The error bars correspond to $\pm 6\%$.

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