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Note

Heat Capacity and Electrical Resistivity of Liquid Niobium Near Its Melting Temperature

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A microsecond-resolution capacitor discharge technique is used to heat niobium specimens rapidly to temperatures several hundred degrees above the melting point. From the measurements of current, voltage, and temperature as a function of time, the heat capacity and electrical resistivity of liquid niobium in the range 2850 to 3200 K were determined. Maximum uncertainties in the results are estimated to be ±5% for heat capacity and ±3% for electrical resistivity.

KEY WORDS: electrical resistivity, heat capacity; high temperatures; niobium; transient techniques.

1. INTRODUCTION

Recently, we reported the results of measurements of the heat of fusion of niobium using a microsecond-resolution capacitor discharge technique [1]. The method was based on rapid resistive self-heating of the specimen by a high-current pulse and measuring the current through the specimen, the voltage across the specimen, and the radiance temperature of the specimen as a function of time. Melting of the specimen was manifested by a plateau in the temperature versus time data. The time integral of the power absorbed by the specimen during melting yielded the heat of fusion. The melting period was determined from the intersection of the functions fitted to the absorbed energy versus radiance temperature data corresponding to premelting, melting, and postmelting periods.

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Data in the postmelting period extended several hundred degrees above the melting temperature. The objective of this note is to utilize those data to determine the heat capacity and electrical resistivity of liquid niobium near its melting temperature.

2. RESULTS

Heat capacity is related to the temperature derivative of absorbed energy by the specimen. In order to evaluate the derivative, it is necessary to convert the measured radiance temperatures to true temperatures. This process requires a knowledge of the normal spectral emittance of the specimen. Normal spectral emittance is related to true and radiance temperatures according to the Wien's radiation equation:

$$\frac{1}{T}-\frac{1}{T_r}=\frac{\lambda \ln \varepsilon_\lambda}{c_2} \tag{1}$$

where T is the true temperature and T_r is the radiance temperature, both in K, c_2 is the second radiation constant (1.4388×10^{-2} m · K), λ is the wavelength of radiation, and ε_λ is the normal spectral emittance of the specimen at wavelength λ. Radiance temperatures were measured with a microsecond-resolution pyrometer [2] at 654 nm (bandwidth, 30 nm).

The quantity ε_λ in Eq. (1) was evaluated at the melting temperature for each specimen using the results of the radiance temperature at the melting point determined earlier [1] and the true melting temperature of niobium, 2750 K [3]. The radiance temperature at the melting point and the corresponding normal spectral emittance for each specimen are given in Table I. Radiance temperatures of each liquid specimen were converted to true temperatures using Eq. (1), assuming that the normal spectral emittance of the liquid was independent of temperature and equal to that determined at the melting temperature.

For each experiment, using the data on current and voltage, energy absorbed by the specimen above an arbitrary temperature (2600 K) as a function of true temperature was plotted for temperatures up to 3200 K, as illustrated in Fig. 1. The results of absorbed energy for each experiment were fitted by a linear function in terms of true temperature over the range 2850 to about 3200 K by the least-squares method. Heat capacity for the liquid specimen was determined from the slope of this function. The results for the heat capacity of the liquid specimens are given in Table I. The average for the six specimens yields a value of 40.8 J · mol^{-1} · K^{-1}, with a standard deviation of 0.2 J · mol^{-1} · K^{-1} and a maximum absolute deviation of 0.3 J · mol^{-1} · K^{-1}.

Table I. Experimental Results on the Heat Capacity, C_p, of Liquid Niobium in the Range 2850 to 3200 K[a]

Specimen No.	T_r (K)	ε_λ	C_p ($J \cdot mol^{-1} \cdot K^{-1}$)	SD (%)[b]
1	2414.4	0.329	40.5	0.20
2	2408.6	0.321	40.7	0.19
3	2413.3	0.327	41.0	0.25
4	2411.5	0.325	40.8	0.12
5	2410.5	0.324	40.7	0.17
6	2415.3	0.330	40.9	0.18

[a] The values of the quantities T_r (radiance temperature) and ε_λ (normal spectral emittance at 654 nm) correspond to the start of melting.

[b] Percentage standard deviation of an individual point from the smooth absorbed energy versus true temperature function (linear) obtained by the least-squares method.

It should be noted that data in the 100 K range above the melting temperature (2750 to 2850 K) were not considered in the above fits. The reason for this is that absorbed energy versus temperature (Fig. 1) showed a rounding, especially during the initial part, in this region. This behavior was observed in all the experiments, and it may possibly be due to non-equilibrium effects. Additional work in this area should prove to be informative and valuable.

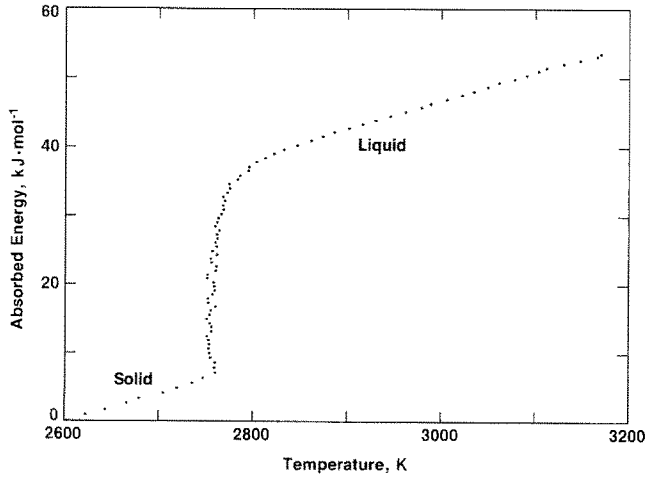

Fig. 1. Energy absorbed by a niobium specimen above 2600 K as a function of temperature for a typical experiment.

Considering the uncertainties in the experimental data (discussed in detail elsewhere [1]) and the additional uncertainties that arise due to the determination of the slope of absorbed energy versus temperature function and the conversion of radiance to true temperatures, the overall uncertainty in the reported heat capacity is estimated to be not more than $\pm 5\%$.

It may be concluded that the heat capacity of liquid niobium in the range 2850 to 3200 K is 40.8 $J \cdot mol^{-1} \cdot K^{-1}$, with a maximum uncertainty of $\pm 5\%$.

The value of the heat capacity for liquid niobium reported in this work is about 0.5% higher than that given by Bonnell [4], 2% lower than that given by Betz and Frohberg [5], and 14 and 28% lower than the values reported by Gallob et al. [6] and Shaner et al. [7], respectively. Mozharov and Savvatimskii [8] have reported a decreasing heat capacity from approximately 42 to about 38 $J \cdot mol^{-1} \cdot K^{-1}$ in the range 2800 to 3200 K.

Measurements of the heat capacity of solid niobium up to 2700 K performed with a millisecond-resolution pulse-heating technique have been reported earlier [9]. Extrapolation of the results to the melting temperature (2750 K [3]) yields a value of 43.4 $J \cdot mol^{-1} \cdot K^{-1}$ for the solid niobium. Comparison of the values for the solid (43.4 $J \cdot mol^{-1} \cdot K^{-1}$) and for the liquid (40.8 $J \cdot mol^{-1} \cdot K^{-1}$) niobium at its melting temperature indicates a decrease in heat capacity by about 6% upon melting.

True temperature data were also used to express the electrical resistivity of liquid niobium. The variation of the electrical resistivity of niobium as a function of temperature in the range 2600 to 3200 K for a typical experiment is shown in Fig. 2. As may be seen in Fig. 2, the resistivity of liquid niobium near its melting temperature is almost constant. The resistivity data for liquid niobium for all the experiments were grouped together and were fitted by a linear function in temperature using the least-squares method. The linear function for the electrical resistivity of liquid niobium in the range 2800 to 3200 K is (SD = 0.3%)

$$\rho = 92.97 + 0.002730\, T \tag{2}$$

where T is in K and ρ is in $\mu\Omega \cdot$ cm. The total uncertainty in the electrical resistivity is estimated to be not more than $\pm 3\%$.

The above relation yields a resistivity of 100.6 $\mu\Omega \cdot$ cm at 2800 K and 101.7 $\mu\Omega \cdot$ cm at 3200 K. These values are, respectively, about 2 and 4% lower than those given by Shaner et al. [7] and are, respectively, about 7 and 10% lower than the values reported by Gallob et al. [6] for the same temperatures. When extrapolated to the melting temperature, Eq. (2) yields a resistivity of 100.5 $\mu\Omega \cdot$ cm, which is in good agreement with the value of 100.6 $\mu\Omega \cdot$ cm obtained previously [1] using the radiance temperature data.

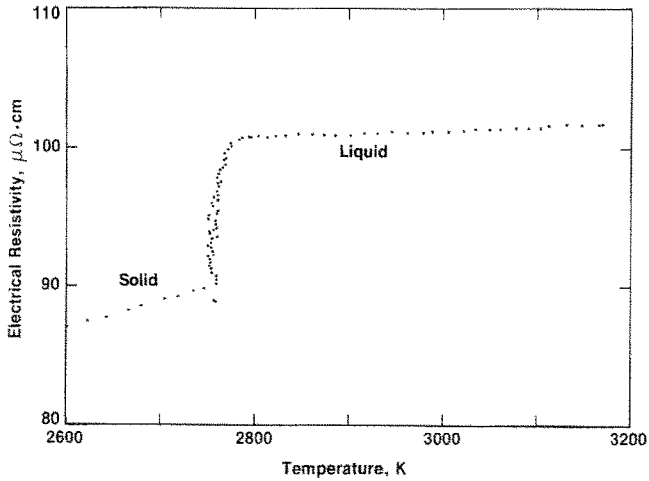

Fig. 2. Variation of the electrical resistivity of a niobium specimen as a function of temperature for a typical experiment.

The results reported in this note suggest that the microsecond-resolution capacitor discharge technique can be used to obtain reliable data on the heat capacity and electrical resistivity of high-melting point liquid metals near their melting temperatures. Successful extension of the measurements to temperatures much higher than the melting temperature requires development of techniques for the accurate determination of the true temperature of the specimen.

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