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Note

Investigation of the Heating Dynamics and Properties of Liquid Tungsten

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The dynamics of electrical explosion of tungsten wires under water in microsecond times was studied. A new optical method for temperature measurement has been developed. For tungsten, uniform heating took place at $10^{11} < j\,(\mathrm{A \cdot m^{-2}}) < 10^{12}$, therefore one can use these regimes for the investigation of properties in the liquid phase. Temperature dependences of enthalpy, electrical resistivity, and specific heat for liquid tungsten are given and compared with literature values.

KEY WORDS: electrical explosion; electrical resistivity; enthalpy; heat of fusion; liquid metal; pyrometry; specific heat; tungsten.

1. INTRODUCTION

Acquiring knowledge on thermophysical properties of liquid metals is of considerable interest to new energy technologies. Unfortunately, direct measurements by steady-state methods are impossible for most metals, especially for refractory metals, because of the extreme temperatures involved.

Fast dynamic techniques have been used, where temperatures are measured by optical methods. A more effective method is self-heating of a wire with an electrical current [1]. This method permits one to investigate a set of thermophysical properties of metals; the limitation of its applicability is due to the loss of specimen uniformity. It is necessary to select the parameters of the specimen and the electric circuit in such a way that one can provide stable heating without losing the radial uniformity of

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the specimen. It was shown in Ref. 2 that there is a radial uniformity of the exploding specimen in the range of parameters $[10^{11} < j\,(\mathrm{A \cdot m^{-2}}) < 10^{12}]$ used. We can see z-instabilities directly and avoid them by choosing proper parameters for the specimen and the electrical circuit.

2. BRIEF DESCRIPTION OF THE SYSTEM

Wire specimens (length, 87 mm; diameter, 0.35 mm) were heated by a current pulse from a capacitor bank ($6\,\mu$F, $4.5\,\mu$H, 20 kV) in a water-filled vessel. The specimen was submerged in water to prevent shunt paths around the specimen. The heating current was measured using a coaxial resistive shunt, and the potential drop across the specimen was measured with a capacitive voltage divider. A direct compensating voltage provided the correction for the inductive component of the voltage, assuming that the inductive signal resulting from changing sample geometry was negligible.

A fast bichromatic pyrometer was used to perform temperature measurements; the pyrometer views a circular spot 1 mm in diameter. The radiance from the heated specimen was focused onto the aperture plane, then it was collimated and after that it was directed onto an optical dividing cube to form two optical channels. Each channel had an interference filter with different bandpasses. In the present work, six filters were used to cover the range of measured temperatures (wavelength centered at 415, 467, 530, 567, 606, and 656 nm, with narrow-band $\Delta\lambda_i \sim 10$ nm) to cover the entire range of the spectral sensitivity of the detectors used. The specimen radiance was measured with photomultipliers. The known temperature of a recognizable feature such as melting was used to calibrate the pyrometer. All voltage, current, and pyrometer data were recorded by storage oscilloscopes providing time resolution to a fraction of a microsecond; such a time resolution was desirable for investigations of liquid metals. The error in measurements was less than 8%. A spark gap was used as a switch to start the experiments.

3. DETAILS OF TEMPERATURE MEASUREMENTS

The thermal state of the specimen can be characterized by a conditional temperature, the so-called integral color temperature (similar to the one in Ref. 3):

$$\frac{\int_{a_i}^{d_i} \varepsilon(\lambda, T)\, r(\lambda, T)\, \psi_{1i}(\lambda)\, d\lambda}{\int_{a_j}^{d_j} \varepsilon(\lambda, T)\, r(\lambda, T)\, \psi_{2j}(\lambda)\, d\lambda} = \frac{\int_{a_i}^{d_i} r(\lambda, T_{ic})\, \psi_{1i}(\lambda)\, d\lambda}{\int_{a_j}^{d_j} r(\lambda, T_{ic})\, \psi_{2j}(\lambda)\, d\lambda} \tag{1}$$

where $\varepsilon(\lambda, T)$ is the normal spectral emissivity, $r(\lambda, T)$ is the spectral density of the blackbody, T_{ic} is the integral color temperature; ψ_{1i} and ψ_{2j} are the apparatus functions of the pyrometer channels; and $(a_i, d_i) = (\lambda_i - 0.5\Delta\lambda_i, \lambda_i + 0.5\Delta\lambda_i)$ is the working range of the ith interference filter.

For the spectral density of the blackbody, the Planck formula is used to determine the integral color temperature from Eq. (1):

$$r(\lambda, T) = \frac{C_1}{\lambda^5}\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]^{-1} \tag{2}$$

where C_1 and C_2 are the first and second radiation constants, respectively.

Here, the ratio of two pyrometer signals is used, therefore it is sufficient to have only the relative calibration of the channel sensitivities [4]:

$$\frac{b_1(\lambda_i)}{b_2(\lambda_j)} = S_{ij}\frac{\int_{a_i}^{d_i} r(\lambda, T_{ic})\,\psi_{1i}(\lambda)\,d\lambda}{\int_{a_j}^{d_j} r(\lambda, T_{ic})\,\psi_{2j}(\lambda)\,d\lambda} \tag{3}$$

where b_i is the signal of the ith pyrometer channel, and S_{ij} is the ratio of the relative calibration of the pyrometer channels for each pair of filters.

T_{ic} is the root of Eq. (3) with the right-hand side calculated by numerical integration. For determining a temperature with minimum error, it is necessary to use a pyrometer signal from the nearest-neighbor bandpass of filters, as the difference in emissivities for nearest-neighbor wavelengths will decrease with decreasing wavelength difference. If the temperature-dependent part of emissivities $\varepsilon(\lambda, T)$ is equal to a constant or is the same for different bandpasses, one can use all pairs of filters for determining the temperature.

Accurate estimation of the temperature measurement error is rather difficult.

4. RESULTS

Figure 1 shows our results for enthalpy plotted as a function of temperature. The specific enthalpy as a function of time is given by $H(t) = m^{-1}\int_0^t I(\tau)\,V(\tau)\,d\tau$, where m is the specimen mass, $I(t)$ is the heating current, and $V(t)$ is the sample voltage drop. For comparison, the data obtained by Hixson and Winkler [5] are also given. The best fit to our data for the liquid phase $[3800 \leqslant T\,(\mathrm{K}) \leqslant 5800]$ is $H = (-0.24 + 2.92 \times 10^{-4} T)$, where H is in $\mathrm{MJ \cdot kg^{-1}}$.

As temperature varies linearly with enthalpy in the liquid phase, we can conclude that the specific heat c_p does not depend on the temperature. Our value of $c_\mathrm{p} = (\partial H/\partial T)_\mathrm{p}$ for liquid tungsten is $292 \pm 20\ \mathrm{J \cdot kg^{-1} \cdot K^{-1}}$, in

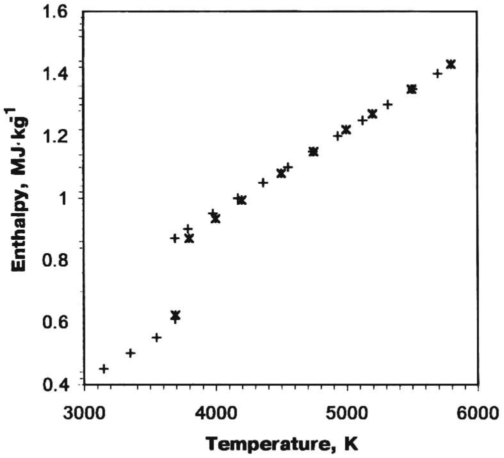

Fig. 1. Enthalpy as a function of temperature for tungsten. 𝔛, present work; + [5].

good agreement with the values obtained by other authors: 262 [5], 300 [6], and 310 $J \cdot kg^{-1} \cdot K^{-1}$ [7]. Our value for the heat of fusion of tungsten is 0.247 $MJ \cdot kg^{-1}$, which is also in good agreement with the values reported: 0.254 [6], 0.26 [5], and 0.275 $MJ \cdot kg^{-1}$ [7].

Figure 2 shows the electrical resistivity data plotted against temperature. Our value for liquid tungsten resistivity changes from 1.398 to 1.45 $\mu\Omega \cdot m$ (in the range of temperatures from melting to boiling); other

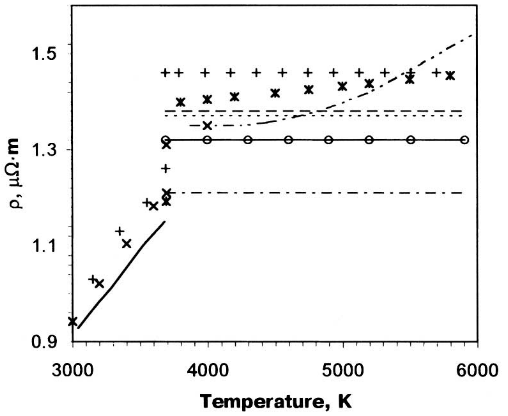

Fig. 2. Electrical resistivity of tungsten. 𝔛, present work; + [5]; —— [6]; ---- [7]; —— [8]; —·— [9]; × [10]; —— [11]; —· ·— [12].

authors give the following values: 1.46 [5], 1.38 [6], 1.37 [7], 1.32 [8]; and 1.21 [9] $\mu\Omega \cdot \mathrm{m}$. Our value for the resistivity thermal coefficient for liquid tungsten is $(2 \pm 0.2) \times 10^{-5}\ \mathrm{K}^{-1}$; thus the resistivity ratio is given by $\rho/\rho_0 = 1 + 2 \times 10^{-5}(T - 3800)$, where $\rho_0 = 1.398\ \mu\Omega \cdot \mathrm{m}$, and $3800 \leqslant T(\mathrm{K}) \leqslant 5800$.

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