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Heat Capacity and Electrical Resistivity of Nickel in the Range 1300–1700 K Measured with a Pulse Heating Technique

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Measurements of the heat capacity and electrical resistivity of nickel in the temperature range 1300–1700 K by a subsecond duration pulse heating technique are described. The results are expressed by the relations:

$$C_p = 21.735 + 9.8200 \times 10^{-3}T$$

$$\rho = 18.908 + 2.3947 \times 10^{-2}T$$

where C_p is in $\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$, ρ is in $\mu\Omega \cdot \mathrm{cm}$, and T is in K. Estimated maximum uncertainties in the measured properties are 3% for heat capacity and 1% for electrical resistivity.

KEY WORDS: electrical resistivity; heat capacity; high temperatures; nickel; pulse heating technique.

1. INTRODUCTION

In this paper, application of a pulse heating technique to the measurements of heat capacity and electrical resistivity of nickel in the temperature range 1300–1700 K is described. The method is based on rapid resistive self-heating of the specimen from room temperature to high temperatures (up to near the melting temperature) in less than 1 s by the passage of an electrical current pulse through it; and on measuring, with millisecond resolution, current through the specimen, potential drop across the specimen, and the

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specimen temperature. Details regarding the construction and operation of the measurement systems, the methods of measuring experimental quantities, and other pertinent information, such as formulation of relations for properties, etc. are given in earlier publications [1,2].

2. MEASUREMENTS

The measurements were performed on three tubular specimens fabricated from cylindrical rods by an electroerosion technique. Nominal dimensions of the tubes were: length, 75 mm; outside diameter, 6.4 mm; wall thickness, 0.5 mm. The results of a typical analysis furnished by the manufacturer indicated that the material was $99.98^{+}\%$ pure with the following impurities in ppm by mass: Fe, 30: O, 20; N, 13; C, 8; Sn < 15; In < 6; Sr < 5; Cl, Ge, Nd, S, Se, Sm, Ta, Te, < 3 each; the total amount of all other detected elements was less than 20 ppm, each element being below the 1 ppm limit.

The response of the high-speed photoelectric pyrometer [3] was optimized by dividing the temperature interval of the measurements (1300–1700 K) into three ranges. One experiment per specimen was performed in each temperature range. The heating rate was varied depending on the temperature range by adjusting the value of the resistance in series with the specimen; typically, the heating rate was in the range 2400–3400 $K \cdot s^{-1}$. Duration of the current pulse was in the range 500–600 ms. All the experiments were conducted with the specimen in a vacuum environment of about 1.3×10^{-3} Pa ($\sim 10^{-5}$ torr). Prior to the experiments, the high-speed pyrometer was calibrated against a tungsten filament reference lamp which, in turn, had been calibrated against the NBS Photoelectric Pyrometer by the Radiometric Physics Division at NBS. All temperatures reported in this work are based on the International Practical Temperature Scale of 1968 [4].

3. RESULTS

The data on voltage, current, and temperature within each temperature range were fitted by second-degree polynomial functions for each quantity in terms of time by the least squares method. The functions were then used to compute the values of heat capacity and electrical resistivity corresponding to each experiment; the results are given in Tables AI and AII of the Appendix. The final values for the properties were obtained by fitting the results in the Appendix by polynomials in temperature by the least squares method. The results are presented at 50 K temperature intervals in Table I.

Table I. Smoothed Heat Capacity and Electrical Resistivity of Nickel According to Eqs. (1) and (2)

T (K)	C_p ($J \cdot mol^{-1} \cdot K^{-1}$)	ρ ($\mu\Omega \cdot cm$)
1300	34.50	50.04
1350	34.99	51.24
1400	35.48	52.43
1450	35.97	53.63
1500	36.46	54.83
1550	36.96	56.03
1600	37.45	57.22
1650	37.94	58.42
1700	38.43	59.62

It may be noted that in all computations, the geometrical quantities of the specimen are based on their room temperature (298 K) dimensions.

3.1. Heat Capacity

Heat capacity was computed using the data taken during the heating period by means of the relation $C_p = ei/nT'$, where e is the voltage between the voltage probes, i the current, n the number of moles, and T' the heating rate of the specimen. A correction was made for the radiative heat loss from the specimen based on the data taken during the initial cooling period of the specimen. This correction amounted to about 1% at 1300 K and about 2% at 1700 K. The function that represents the results for heat capacity (standard deviation = 0.6%) in the temperature range 1300–1700 K is

$$C_p = 21.735 + 9.8200 \times 10^{-3} T \tag{1}$$

where C_p is in $J \cdot mol^{-1} \cdot K^{-1}$ and T is in K. In the computation of heat capacity, the atomic weight of nickel was taken as 58.71. Figure 1 shows the deviation of the measured heat capacity values for the three specimens from the smooth function defined by Eq. (1).

3.2. Electrical Resistivity

The electrical resistivity of the specimen was computed by means of the relation $\rho = RA/L$, where R is the resistance, A the cross-sectional area, and L the length of the specimen between the voltage probes. The cross-sectional area was obtained from the density of nickel (8.902 $g \cdot cm^{-3}$) and the measurement of the specimen weight. The function that

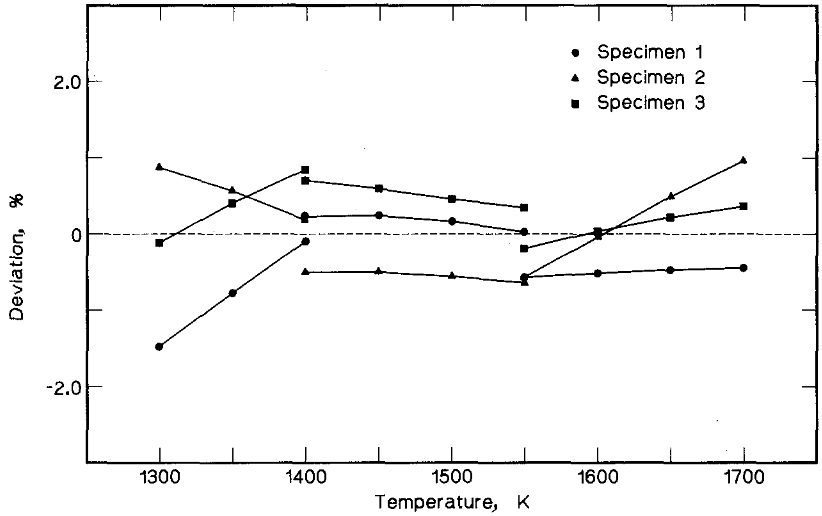

Fig. 1. Deviation of heat capacity results for three specimens of nickel from the smooth function given by Eq. (1).

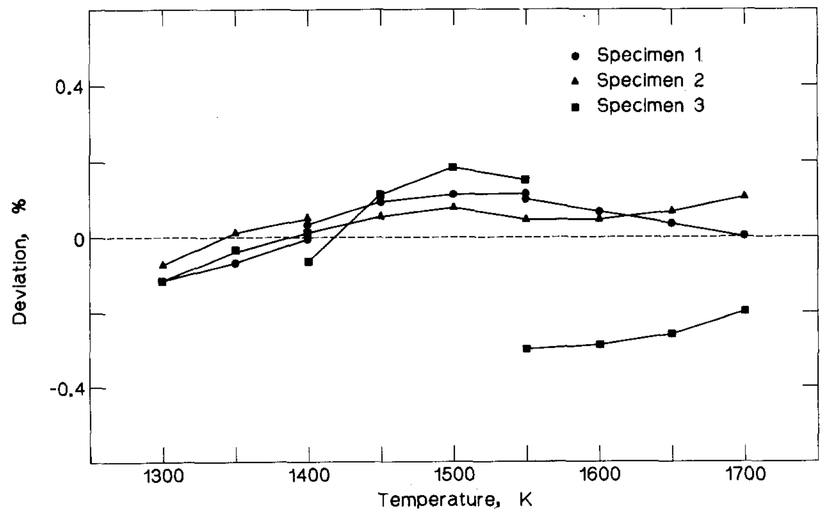

Fig. 2. Deviation of electrical resistivity results for three specimens of nickel from the smooth function given by Eq. (2).

represents the results for electrical resistivity (standard deviation = 0.1%) in the temperature range 1300–1700 K is

$$\rho = 18.908 + 2.3947 \times 10^{-2}T \tag{2}$$

where ρ is in $\mu\Omega \cdot$cm and T is in K. The deviation of the measured resistivity values for the three specimens from the smooth function defined by Eq. (2) is shown in Fig. 2. Prior to the pulse experiments, a Kelvin bridge was used to measure the electrical resistivity of the specimen at 295 K yielding an average value of 7.54 $\mu\Omega \cdot$cm with an average absolute deviation of 0.3% and a maximum absolute deviation of 0.4%.

3.3. Estimate of Errors

The methods of estimating errors in the measured and computed quantities have been discussed in detail in an earlier publication [1]. Items in the error analysis were recomputed whenever the present conditions differed from those in ref. [1]. The maximum uncertainty in the reported values is estimated to be 3% in heat capacity and 1% in electrical resistivity.

4. DISCUSSION

The heat capacity and electrical resistivity of nickel measured in this work are presented and compared graphically with those reported in the literature in Figs. 3 and 4, respectively. Heat capacity data at temperatures in the present range have also been obtained by Krauss and Warncke [5] and by Vollmer et al. [6], using adiabatic calorimetry, and by Kollie [7] using a slow pulse heating method. The results of Vollmer et al. are in good agreement (better than 1%) with the present work whereas the data obtained in the other two investigations are about 4% higher. Measurements by Novikov [8] using an adiabatic method and by Ewert [9] using drop calorimetry have yielded heat capacity data at temperatures up to about 1250 and 1275 K, respectively. The trend of these data with increasing temperature is different than that of the present work, though extrapolations to 1300 K yield respective values which are only about 2 and 3% lower than the present value for heat capacity.

The electrical resistivity results reported by Kollie [7] and by Powell et al. [10] are, respectively, about 1 and 1.5% lower than our results whereas the data reported by Laubitz et al. [11] when extrapolated to 1300 K are about 2% lower. However, the differences are within the combined experimental (and extrapolation) errors. The lower values of resistivity obtained

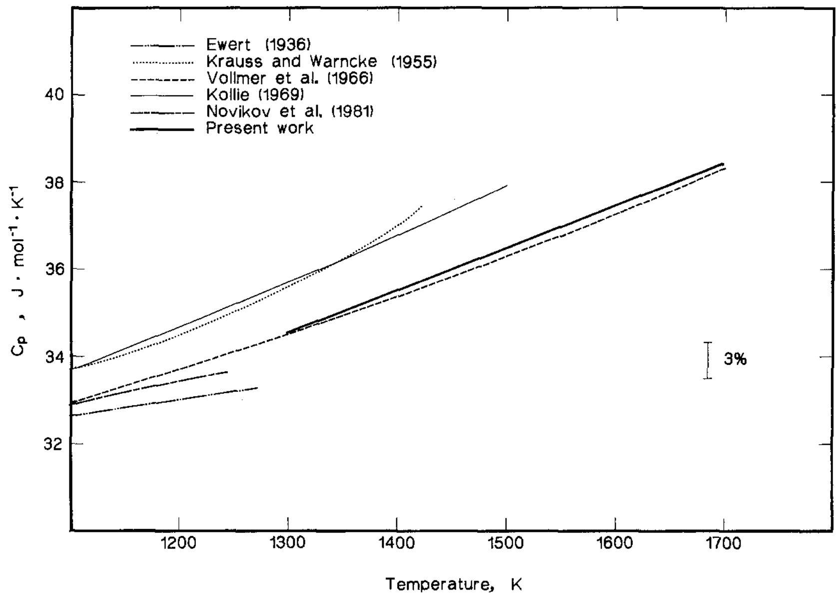

Fig. 3. Heat capacity of nickel: present work and data reported in the literature.

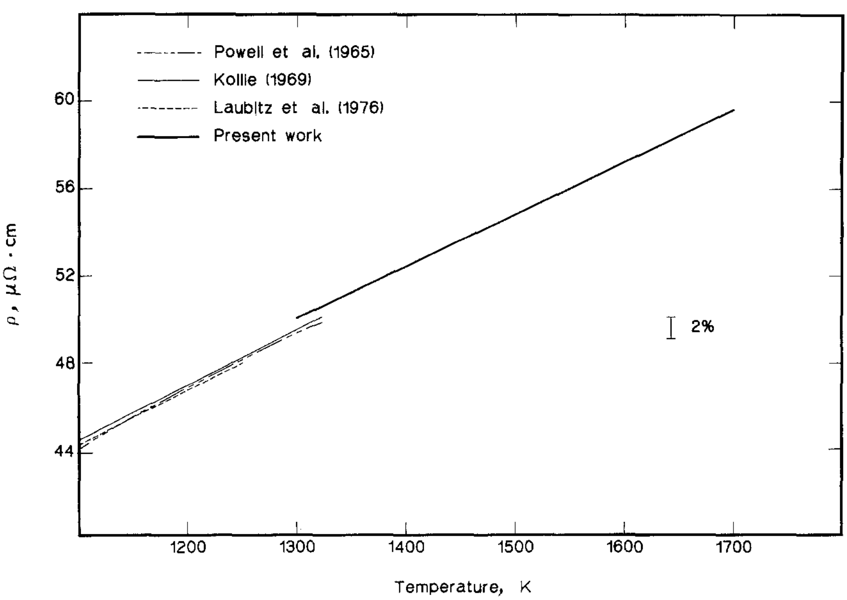

Fig. 4. Electrical resistivity of nickel: present work and data reported in the literature.

in the earlier investigations may be partly due to extensive annealing of the specimens used in the measurements: the specimen (> 99.89% pure) used by Kollie was annealed at 1100 K for 24 hr, and Laubitz et al. annealed their specimen (99.99^+% pure) at 1400 K for 2 hr, whereas the present specimens (99.98^+% pure) were each subjected to a pulse heating to about 1500 K, prior to the measurements. Specimens of higher purity should also yield lower values of resistivity. Powell et al. did not give details concerning the heat treatment and purity of the specimen used in their measurements.

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APPENDIX

Table AI. Experimental Results[a] for the Heat Capacity of Nickel

	Specimen 1		Specimen 2		Specimen 3	
T (K)	C_p ($J \cdot mol^{-1} \cdot K^{-1}$)	ΔC_p (%)	C_p ($J \cdot mol^{-1} \cdot K^{-1}$)	ΔC_p (%)	C_p ($J \cdot mol^{-1} \cdot K^{-1}$)	ΔC_p (%)
Range I						
1300	33.99	− 1.48	34.80	+ 0.87	34.47	− 0.09
1350	34.72	− 0.78	35.19	+ 0.57	35.14	+ 0.42
1400	35.45	− 0.09	35.55	+ 0.19	35.79	+ 0.87
Range II						
1400	35.57	+ 0.25	35.30	− 0.52	35.74	+ 0.72
1450	36.06	+ 0.24	35.79	− 0.51	36.19	+ 0.60
1500	36.52	+ 0.15	36.26	− 0.56	36.63	+ 0.45
1550	36.96	+ 0.01	36.71	− 0.67	37.08	+ 0.34
Range III						
1550	36.74	− 0.58	36.74	− 0.58	36.88	− 0.21
1600	37.25	− 0.53	37.42	− 0.07	37.46	+ 0.03
1650	37.75	− 0.50	38.10	+ 0.43	38.02	+ 0.22
1700	38.25	− 0.47	38.79	+ 0.94	38.56	+ 0.34

[a] ΔC_p is the percentage deviation of the individual results from the smooth function defined by Eq. (1).

Table AII. Experimental Results[a] for the Electrical Resistivity of Nickel

	Specimen 1		Specimen 2		Specimen 3	
T (K)	ρ ($\mu\Omega \cdot$ cm)	$\Delta\rho$ (%)	ρ ($\mu\Omega \cdot$ cm)	$\Delta\rho$ (%)	ρ ($\mu\Omega \cdot$ cm)	$\Delta\rho$ (%)
Range I						
1300	49.98	− 0.12	50.00	− 0.08	49.98	− 0.12
1350	51.20	− 0.07	51.24	+ 0.01	51.22	− 0.03
1400	52.43	− 0.01	52.46	+ 0.05	52.44	+ 0.01
Range II						
1400	52.45	+ 0.03	52.44	+ 0.01	52.40	− 0.06
1450	53.68	+ 0.09	53.66	+ 0.05	53.69	+ 0.11
1500	54.89	+ 0.11	54.87	+ 0.08	54.93	+ 0.19
1550	56.09	+ 0.11	56.05	+ 0.04	56.11	+ 0.15
Range III						
1550	56.08	+ 0.10	56.05	+ 0.04	55.86	− 0.30
1600	57.26	+ 0.06	57.25	+ 0.05	57.06	− 0.28
1650	58.44	+ 0.03	58.46	+ 0.07	58.27	− 0.26
1700	59.62	+ 0.01	59.68	+ 0.10	59.50	− 0.20

[a] $\Delta\rho$ is the percentage deviation of the individual results from the smooth function defined by Eq. (2).

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