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Thermophysical Measurements on Tungsten–3 (Wt %) Rhenium Alloy in the Range 1500–3600 K by a Pulse Heating Technique

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Simultaneous measurements of the specific heat capacity, c_p, electrical resistivity, ρ, and hemispherical total emittance, ε, of tungsten–3 (wt %) rhenium alloy in the temperature range 1500–3600 K by a subsecond-duration pulse heating technique are described. The results are expressed by the relations

$$c_p = 0.30332 - 2.8727 \times 10^{-4}\, T + 1.9783 \times 10^{-7}\, T^2 - 5.6672 \times 10^{-11}\, T^3 + 6.5628 \times 10^{-15}\, T^4,$$

$$\rho = -24.261 + 8.1924 \times 10^{-2}\, T - 3.7656 \times 10^{-5}\, T^2 + 1.1850 \times 10^{-8}\, T^3 - 1.3229 \times 10^{-12}\, T^4,$$

$$\varepsilon = 0.1945 + 5.881 \times 10^{-5}\, T,$$

where T is in K, c_p is in $J \cdot g^{-1} \cdot K^{-1}$, and ρ is in $\mu\Omega \cdot cm$. The melting temperature (solidus temperature) was also measured and was determined to be 3645 K. Uncertainties of the measured properties are estimated to be not more than $\pm 3\%$ for specific heat capacity, $\pm 1\%$ for electrical resistivity, $\pm 5\%$ for hemispherical total emittance, and ± 20 K for the melting temperature.

KEY WORDS: dynamic techniques; electrical resistivity; high temperatures; melting temperature; specific heat capacity; thermal emittance; tungsten–rhenium alloy.

1. INTRODUCTION

In this paper, the application of a pulse heating technique to measurements of selected thermophysical properties (specific heat capacity, electrical resistivity, hemispherical total emittance, melting temperature[2]) of the alloy

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[2] An alloy has a melting range instead of a melting temperature. For convenience, in the present work the solidus temperature of the alloy is referred to as the melting temperature.

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tungsten–3 (wt %) rhenium at temperatures above 1500 K is described. The measurement technique has been used successfully to obtain thermal properties of a number of refractory metals and alloys at high temperatures [1].

The method is based on rapid resistive self-heating of the specimen from room temperature to its melting point in less than 1 s by the passage of an electrical current pulse through it; and on simultaneously measuring the specimen temperature, and the current through and voltage across the specimen. The temperature is measured by means of a high-speed photoelectric pyrometer [2]. The current through the specimen is determined by measuring the voltage across a standard resistance in series with the specimen. The voltage across the middle one-third of the specimen is measured between spring-loaded knife edge probes. These quantities are recorded digitally every 0.4 ms, with a full-scale resolution of about 1 part in 8000. Details regarding the construction and operation of the measurement system and other pertinent information such as formulation of relations for properties, error analysis, etc., are given in earlier publications [3, 4].

2. MEASUREMENTS

2.1. Specimen

The measurements of specific heat capacity, electrical resistivity, hemispherical total emittance, and melting temperature were performed on a tungsten–3 (wt %) rhenium specimen in the form of a tube. The tube was fabricated by a vapor deposition technique. The nominal dimensions of the tube were as follows: length, 76 mm; outside diameter, 6.4 mm; and wall thickness, 0.5 mm. A small rectangular sighting hole (0.5×1 mm) was fabricated through the wall at the middle of the tube, thereby approximating a blackbody cavity for the pyrometric temperature measurements. The outer surface of the specimen was polished to reduce heat loss due to thermal radiation.

A spectrochemical analysis was performed on portions of the specimen after completion of the pulse experiments. The major constituent in the specimen, other than tungsten, was found to be rhenium, 3.24% by weight. The impurities were determined to be (ppm by weight): Ta, 100; C, 79; Mo, 60; Cu, 25; F, 20; O, 12; Ni and Fe, 10 each; Si, 7; S and P, 5 each; H, 4; Al and N, 3 each; Zr, <3; Cr and Cl, 2 each; and Co, Sn, and Ti, <2 each. The total amount of all other detected elements was less than 8 ppm, the content of each element being below the 1-ppm limit.

2.2. Procedure

To optimize the operation of the high-speed pyrometer, the temperature interval (1500–3650 K) was divided into seven ranges. The desired heating rate in a given temperature range was achieved by adjusting a resistance in series with the specimen prior to each experiment. The heating rate of the specimen was in the range 3700–6200 $K \cdot s^{-1}$; the current pulse in all cases was less than 600 ms in duration.

The experiments up to 3100 K were conducted with the specimen in a vacuum environment of approximately 10^{-5} Torr (about 1.3×10^{-3} Pa). Additional experiments, in the range 2700 K to the melting temperature of the specimen, were performed with the specimen in an argon environment at slightly above atmospheric pressure. The reason for the use of an argon environment was to suppress possible evaporation of the specimen near and during its melting. There were no significant differences in the results obtained for the cases in the overlapping temperature range (2700–3100 K) where the specimen was in a vacuum or an argon environment, indicating the presence of argon did not affect the measured properties.

Upon completion of the experiments, the high-speed pyrometer was calibrated by means of 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 [5].

3. RESULTS

In all computations, the geometrical quantities were based on their room temperature (293 K) dimensions. The results for specific heat capacity and electrical resistivity obtained from individual experiments are given in Table A1 in the Appendix. The results for hemispherical total emittance are given in Table A2 in the Appendix. The final values for the properties given at 100 K temperature intervals in Table I were computed by fitting (least-squares method) polynomial functions in temperature to the results presented in the Appendix.

3.1. Specific Heat Capacity

Specific heat capacity was computed from data taken during the heating period. The radiative heat loss was about 2% at 1500 K, 14% at 3000 K, and 25% at 3600 K. A correction for this loss was made based on

Table I. Smoothed Values for Specific Heat Capacity, Electrical Resistivity, and Hemispherical Total Emittance of the W-3 (Wt %) Re Alloy Based on Eqs. (1), (2), and (3), Respectively

T (K)	c_p ($J \cdot g^{-1} \cdot K^{-1}$)	ρ^a ($\mu\Omega \cdot cm$)	ε
1500	0.1595	47.20	
1600	0.1610	50.29	
1700	0.1631	53.35	0.294
1800	0.1656	56.42	0.300
1900	0.1685	59.50	0.306
2000	0.1717	62.60	0.312
2100	0.1753	65.73	0.318
2200	0.1791	68.91	0.324
2300	0.1832	72.12	0.330
2400	0.1877	75.38	0.336
2500	0.1924	78.68	0.342
2600	0.1976	82.01	0.347
2700	0.2032	85.36	0.353
2800	0.2093	88.72	0.359
2900	0.2160	92.08	0.365
3000	0.2234	95.40	0.371
3100	0.2317	98.68	0.377
3200	0.2410	101.88	
3300	0.2514	104.98	
3400	0.2631	107.95	
3500	0.2763	110.74	
3600	0.2912	113.32	

[a] Based on the room-temperature (293 K) dimensions of the specimen.

the hemispherical total emittance results obtained during the same experiments. The function for specific heat capacity that represents the results (SD = 0.4 %) in the temperature range 1500–3600 K is

$$c_p = 0.30332 - 2.8727 \times 10^{-4}\, T + 1.9783 \times 10^{-7}\, T^2 - 5.6672 \times 10^{-11}\, T^3 + 6.5628 \times 10^{-15}\, T^4 \quad (1)$$

where T is in K and c_p is in $J \cdot g^{-1} \cdot K^{-1}$.

3.2. Electrical Resistivity

The electrical resistivity was determined from the same experiments that were used to calculate the specific heat capacity. The function for elec-

trical resistivity that represents the results (SD = 0.1 %) in the temperature range 1500 to 3600 K is

$$\rho = -24.261 + 8.1924 \times 10^{-2} T - 3.7656 \times 10^{-5} T^2 + 1.1850 \times 10^{-8} T^3 - 1.3229 \times 10^{-12} T^4 \quad (2)$$

where T is in K and ρ is in $\mu\Omega \cdot$ cm. In the computation of electrical resistivity, the cross-sectional area was obtained from a measurement of specimen weight and from the value of density (19.4 g · cm^{-3}). The measurement, before the pulse experiments, of the electrical resistivity of the specimen with a Kelvin bridge yielded a value of 11.24 $\mu\Omega \cdot$ cm at 293 K.

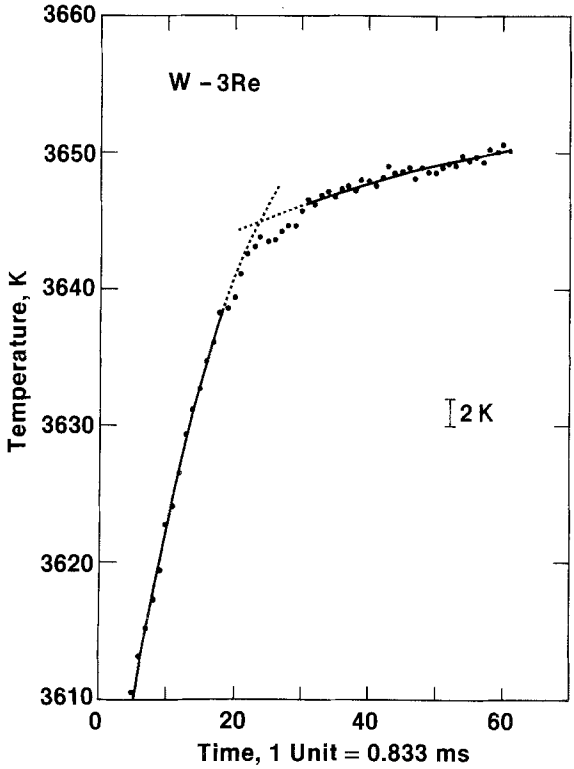

Fig. 1. Variation of the temperature of tungsten–3 (wt %) rhenium alloy as a function of time near and during melting. The melting temperature is obtained from the intersection of the two quadratic functions fitted to temperatures before and during melting of the specimen.

3.3. Hemispherical Total Emittance

Hemispherical total emittance was computed from data taken during both heating and initial free radiative cooling periods. The function for hemispherical total emittance that represents the results (SD = 0.1 %) in the temperature range 1700–3000 K is

$$\varepsilon = 0.1945 + 5.881 \times 10^{-5}\, T \tag{3}$$

where T is in K.

3.4. Melting Temperature

The temperature of the specimen was measured before and during the initial melting period until the specimen collapsed. A significant decrease in the rate of temperature rise before the collapse of the specimen indicated the transition through the solidus temperature. The measured temperatures of the specimen before and during the onset of melting are shown in Fig. 1. The melting temperature (solidus temperature) for the specimen was obtained from the intersection, along the temperature versus time functions, of a quadratic fit to temperatures in the melting region and a quadratic fit to the temperatures before melting, both determined by the least-squares method. The resultant value is 3645 K for the melting temperature of the tungsten–3 (wt %) rhenium alloy.

3.5. Estimate of Errors

The details of estimating errors in measured and computed quantities associated with the present measurement system are given in an earlier

Table II. Summary of the Estimates of Errors

Quantity	Imprecision[a]	Uncertainty[b]
Specific heat capacity	0.4 %	3 %
Electrical resistivity	0.1 %	1 %
Hemispherical total emittance	0.1 %	5 %
Melting temperature	1 K	20 K

[a] Imprecision refers to the standard deviation of a quantity as computed from the difference between the measured value and that from the smooth function obtained by the least-squares method.

[b] Uncertainty refers to the estimated total error (random and systematic).

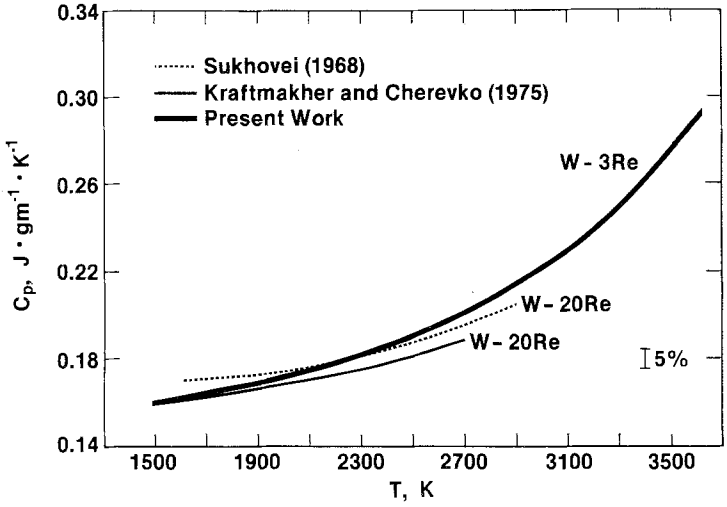

Fig. 2. Specific heat capacity of tungsten–rhenium alloys reported in the literature.

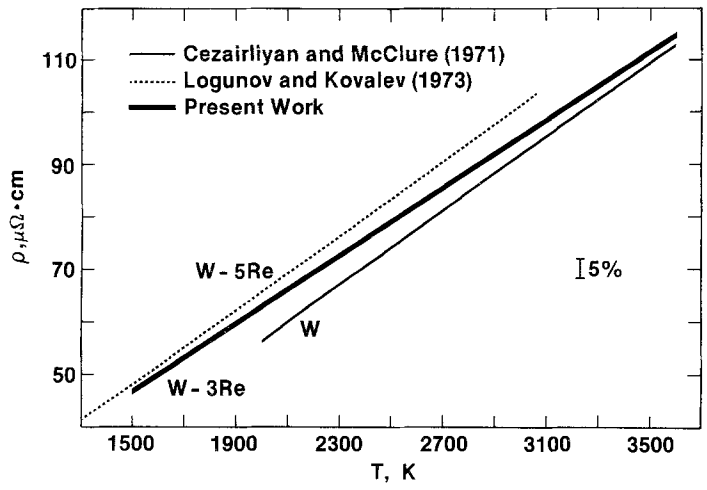

Fig. 3. Electrical resistivity of tungsten–rhenium alloys and of pure tungsten reported in the literature.

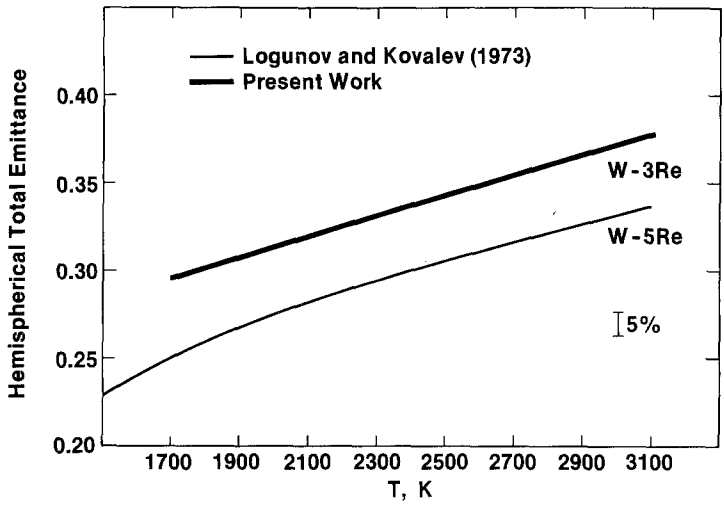

Fig. 4. Hemispherical total emittance of tungsten–rhenium alloys reported in the literature.

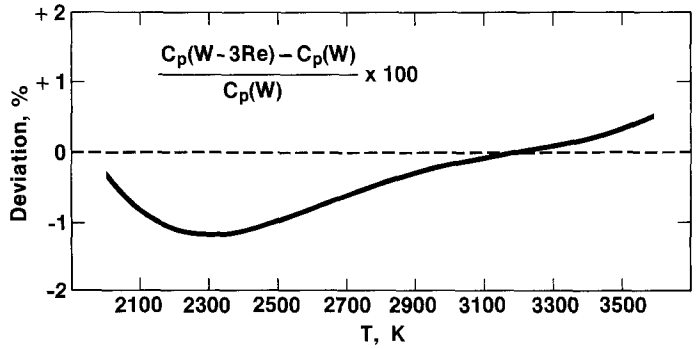

Fig. 5. Deviation of the specific heat capacity of tungsten–3 (wt %) rhenium alloy from that of pure tungsten [6].

publication [4]. In the present work, the specific items were recomputed whenever the conditions differed from those in the earlier publication. The results are summarized in Table II.

4. DISCUSSION

The specific heat capacity, electrical resistivity, and hemispherical total emittance of the tungsten–3 (wt %) rhenium alloy measured in the present work are presented graphically in Figs. 2, 3, and 4, respectively. For comparison purposes, results for pure tungsten and/or other tungsten–rhenium alloys reported in the literature are also included in the figures.

The present values for specific heat capacity are nearly the same as those obtained in earlier measurements on pure tungsten by Cezairliyan and McClure [6], also using the pulse heating system at NBS. The differences, which are well within the experimental error, are given as a deviation plot in Fig. 5. A comparison in Fig. 2 of our specific heat capacity data with those reported by Sukhovei [7] and by Kraftmakher and Cherevko [8] for the tungsten–20 (wt %) rhenium alloy shows that, at temperatures common to the different investigations, the results agree to within the combined experimental errors; however, the data for W-20 Re exhibit a somewhat different trend with changing temperature.

The electrical resistivity values obtained in this work lie between those for the tungsten–5 (wt %) rhenium alloy measured by Logunov and Kovalev [9] and the values reported for pure tungsten by Cezairliyan and McClure [6]. As shown in Fig. 3, the present values are about 2% lower than the W-5 Re data at 1500 K and approximately 6% lower at 3000 K. Our results suggest that the resistivity increment of W-3 Re relative to the resistivity of pure tungsten decreases from about 10% at 2000 K to about 1% as the solidus temperature of the alloy is approached. At 293 K, our value for the resistivity of W-3 Re (11.24 $\mu\Omega \cdot$ cm) is lower than the resistivity of W-5 Re (12.8 $\mu\Omega \cdot$ cm).

As may be seen in Fig. 4, the values of hemispherical total emittance determined from the present measurements on W-3 Re are approximately 10% higher than those reported by Logunov and Kovalev [9] for W-5 Re.

The present value for the solidus temperature of W-3 Re (3645 K) is lower than the melting point of pure tungsten (3695 K) [10], as expected. No literature values for the solidus temperature of the tungsten–3 (wt %) rhenium alloy were found.

APPENDIX

Table A1. Experimental Results for the Specific Heat Capacity and Electrical Resistivity of the W-3 (Wt %) Re Alloy

	Specific heat capacity		Electrical resistivity	
T (K)	c_p ($J \cdot g^{-1} \cdot K^{-1}$)	Δc_p[a] (%)	ρ[b] ($\mu\Omega \cdot cm$)	$\Delta\rho$[c] (%)
Range I				
1500	0.1586	−0.56	47.23	0.07
1550	0.1600	−0.11	48.76	0.03
1600	0.1612	0.12	50.29	0.01
1650	0.1623	0.20	51.81	−0.02
1700	0.1633	0.14	53.34	−0.03
Range II				
1700	0.1627	−0.23	53.36	0.01
1750	0.1645	0.14	54.87	−0.03
1800	0.1662	0.37	56.40	−0.03
1850	0.1678	0.48	57.94	−0.03
1900	0.1692	0.42	59.49	−0.01
Range III				
1900	0.1684	−0.05	59.46	−0.06
1950	0.1702	0.08	61.00	−0.07
2000	0.1720	0.16	62.57	−0.04
2050	0.1736	0.08	64.15	−0.01
2100	0.1752	−0.04	65.75	0.03
Range IV				
2100	0.1745	−0.44	65.74	0.01
2150	0.1768	−0.20	67.33	0.02
2200	0.1789	−0.12	68.93	0.04
2250	0.1810	−0.08	70.53	0.03
2300	0.1830	−0.13	72.14	0.02
2350	0.1848	−0.34	73.76	0.02
Range V				
2350	0.1857	0.15	73.78	0.04
2400	0.1875	−0.09	75.42	0.05
2450	0.1895	−0.27	77.07	0.06
2500	0.1918	−0.33	78.71	0.04
2550	0.1943	−0.34	80.35	0.01
2600	0.1971	−0.25	82.01	0.00

[a] Percentage deviation of the individual results from the smooth function defined by Eq. (1).
[b] Based on the room-temperature (293 K) dimensions of the specimen.
[c] Percentage deviation of the individual results from the smooth function defined by Eq. (2).

Table A1. *(Continued)*

	Specific heat capacity		Electrical resistivity	
T (K)	c_p ($J \cdot g^{-1} \cdot K^{-1}$)	Δc_p [a] (%)	ρ [b] ($\mu\Omega \cdot cm$)	$\Delta\rho$ [c] (%)
2650	0.2003	−0.01	83.67	−0.02
2700	0.2038	0.31	85.34	−0.02
Range VI				
2700	0.2024	−0.38	85.38	0.02
2750	0.2057	−0.22	87.05	0.01
2800	0.2091	−0.08	88.71	−0.01
2850	0.2126	0.02	90.37	−0.03
2900	0.2164	0.19	92.02	−0.06
2950	0.2204	0.36	93.66	−0.09
3000	0.2246	0.53	95.29	−0.12
3050	0.2292	0.77	96.90	−0.15
3100	0.2342	1.08	98.49	−0.19
Range VII				
3100	0.2327	0.43	98.81	0.13
3150	0.2366	0.17	100.40	0.11
3200	0.2407	−0.11	101.97	0.09
3250	0.2452	−0.33	103.52	0.07
3300	0.2500	−0.55	105.04	0.05
3350	0.2553	−0.68	106.52	0.03
3400	0.2611	−0.76	107.97	0.02
3450	0.2677	−0.67	109.37	0.00
3500	0.2752	−0.40	110.73	−0.01
3550	0.2839	0.12	112.03	−0.03
3600	0.2943	1.05	113.25	−0.06

Table A2. Experimental Results for the Hemispherical Total Emittance of the W-3 (Wt %) Re Alloy

T (K)	ε	$\Delta\varepsilon$ [a] (%)
1736	0.297	0.1
1921	0.307	−0.1
2082	0.317	0.0
2359	0.333	−0.1
2696	0.353	0.0
3033	0.373	0.0

[a] Percentage deviation of the individual results from the smooth function defined by Eq. (3).

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