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Selected Electrical Resistivity Values for the Platinum Group of Metals Part III: Ruthenium and Osmium

Improved values obtained for ruthenium and osmium

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Anisotropic and average intrinsic electrical resistivity measurements of ruthenium were evaluated from 10 K to 1600 K and average values above this temperature up to the melting point. For osmium average values were evaluated from 30 K to 273.15 K and anisotropic and average values above this temperature and up to 1600 K.

Introduction

Previous reviews on electrical resistivity were given in Part I for palladium and platinum (1) and in Part II for rhodium and iridium (2).

The elements ruthenium and osmium are both superconducting with transition temperatures of 0.49 ± 0.015 K for ruthenium and 0.66 ± 0.03 K for osmium (3). Both have hexagonal close-packed structures and resistivity values are therefore selected along directions both perpendicular to the *c* axis ($\rho_\perp$) and parallel to the *c* axis ($\rho_{||}$). The average resistivity is then given by $\rho_{avr} = (2\rho_\perp + \rho_{||})/3$. The melting point of ruthenium is a secondary fixed point on the International Temperature Scale of 1990 (ITS-90) at 2606 ± 10 K (4) whilst the melting point of osmium is estimated as being 3400 ± 50 K (5).

Ruthenium

Selected resistivity values at 273.15 K are given in **Table I**. Because of the possibility of preferred orientation in polycrystalline samples only results for single crystals are considered in the selection. On this basis the selected values are an average of the measurements of Powell *et al.* (11), Azhazha *et al.* (12) and Volkenshteyn *et al.* (13).

At 30 K and below selected intrinsic anisotropic and average values are given by the equations of Volkenshteyn *et al.* (10) as Equations (i) to (iii).

Anistropic measurements of Azhazha *et al.* (12) to 25 K lead to identical values at 20 K whilst the average value at 20 K of 0.0019 μΩ cm is in excellent agreement with the value of 0.0017 μΩ cm calculated from the equation of Schriempf and Macinnes (15) (4–20 K).

Between 30 K and 273.15 K for Volkenshteyn *et al.* (10) and below 273.15 K for Azhazha *et al.* (12) and Volkenshteyn *et al.* (13) the anisotropic resistivity measurements were only shown graphically with actual values estimated from these graphs. Average resistivity values of White and Woods (6, 7) (25–295 K) when normalised to the selected value at 273.15 K using the ratio 6.16/6.69 show excellent agreement with average values of Volkenshteyn *et al.*

Table I Electrical Resistivity of Ruthenium at 273.15 K

Authors	Ref.	$\rho_i \perp$, µΩ cm	$\rho_i \parallel$, µΩ cm	$\rho_{i\ avr}$, µΩ cm	Temperature of data
White and Woods	6, 7	–	–	6.69	At 273.15 K
Powell *et al.*	8	–	–	6.54	At 273.15 K. Corrected ρ_0 0.57 µΩ cm
Tainsh and White	9	–	–	6.72	At 273.15 K. Corrected ρ_0 0.02 µΩ cm
Volkenshteyn *et al.*	10	7.15	5.26	6.52	At 273.15 K. Corrected $\rho_0 \perp$ 0.10 µΩ cm; $\rho_0 \parallel$ 0.09 µΩ cm
Powell *et al.*	11	6.75	5.12	6.21	Interpolated 200–400 K. Corrected for both axes by ρ_0 0.07 µΩ cm
Azhazha *et al.*	12	6.61	5.14	6.12	At 273.15 K
Volkenshtein *et al.*	13	6.65	5.15	6.15	At 273.15 K. Estimated by Bass (14) from a graphical representation
Selected		**6.67±0.08**	**5.14±0.02**	**6.16±0.05**	**At 273.15 K**

(13) estimated at 80 K and above with the average bias being only 0.01 µΩ cm low at 120 K and above. The measurements of Volkenshteyn *et al.* (13) were therefore selected to 260 K, combined with the selected values at 273.15 K and fitted to Equations (iv) to (vi) to represent the range from 100 K to 273.15 K. The overall accuracies as standard deviations of ±0.03 µΩ cm and ±0.02 µΩ cm respectively indicate a satisfactory degree of correlation considering that the values were only estimated.

Below 100 K the measurements of White and Woods (6, 7) over the range 40 to 60 K were converted from average to anisotropic values using ratios of $\rho_i \parallel / \rho_i \perp$ determined from the measurements of Volkenshteyn *et al.* (10) after correction for ρ_0 whilst values of $\rho_i \perp$ and $\rho_i \parallel$ at 70 K and 90 K were estimated by interpolation.

In comparison with Equations (iii) and (iv) the estimated measurements of Azhazha *et al.* (12) show a maximum deviation of 0.19 µΩ cm low at 180 K along both axes whilst after correction for residual resistivity the measurements of Volkenshteyn *et al.* (10) trend to values at 273.15 K of 0.48 µΩ cm high perpendicular to the *c* axis but only 0.12 µΩ cm high parallel to the *c* axis.

In the high temperature region anisotropic resistivity measurements of Savitskil *et al.* (16) (300–1600 K) were only shown graphically with actual data points given by Savitskil *et al.* (17). These can be made to show satisfactory agreement with the selected values at 273.15 K only when considered over the range 600 K to 1600 K while the values at 300 K and 400 K showed marked deviations and were therefore rejected. After correction for thermal expansion using length values selected by the present author (18) the electrical resistivity values over the range 273.15 K to 1600 K were represented by Equations (vii) to (ix) with derived values given in **Table II**. Along the axes overall accuracies as standard deviations are ±0.27 µΩ cm and ±0.10 µΩ cm respectively.

Average electrical resistivity measurements of Binkele and Brunen (19) (273–1421 K) trend from initially 4.9% high to 0.5% high at 1100 K and then increases to 1.4% high at 1421 K whilst average measurements of Milošević and Nikolić (20) (250–2500 K) trend from initially 7.3% high to 0.7% low at 1600 K. These two sets of measurements differ sharply above 1100 K with the difference reaching 1.7% at 1421 K, the experimental limit of Binkele and Brunen. Since the measurements of Milošević and Nikolić were fitted to a quadratic equation it was found that the values at 2300 K and above showed a reasonable degree of correlation with an extrapolation of Equation (ix) and therefore the selected average value at 1600 K was combined with the high temperature measurements of Milošević and Nikolić at 2300 K, 2400 K and 2500 K and fitted to Equation (x) to give a fairly satisfactory representation of the average electrical resistivity in the range from 1600 K up to the melting point. Values derived from Equation (x) are given in **Table III**.

Percentage deviations from the selected values of the average measurements of Savitskil *et al.*, Binkele

Table II Intrinsic Electrical Resistivity of Ruthenium (10 K to 1600 K)

Temperature, K	$\rho_i \perp$, µΩ cm	$\rho_i \parallel$, µΩ cm	$\rho_{i\,avr}$, µΩ cm	Temperature, K	$\rho_i \perp$, µΩ cm	$\rho_i \parallel$, µΩ cm	$\rho_{i\,avr}$, µΩ cm
10	0.0003	0.0003	0.0003	230	5.30	4.12	4.91
20	0.0020	0.0017	0.0019	240	5.62	4.36	5.20
30	0.0093	0.0079	0.0088	250	5.94	4.60	5.49
40	0.038	0.030	0.035	260	6.25	4.83	5.78
50	0.11	0.08	0.10	270	6.57	5.07	6.07
60	0.25	0.17	0.22	273.15	6.67	5.14	6.16
70	0.42	0.33	0.39	280	6.91	5.28	6.37
80	0.63	0.52	0.59	290	7.26	5.48	6.67
90	0.89	0.73	0.84	300	7.61	5.68	6.96
100	1.20	0.96	1.12	400	11.1	7.74	9.97
110	1.51	1.21	1.41	500	14.6	9.89	13.0
120	1.83	1.46	1.71	600	18.0	12.1	16.1
130	2.14	1.71	2.00	700	21.5	14.4	19.2
140	2.46	1.95	2.29	800	25.0	16.8	22.3
150	2.77	2.20	2.58	900	28.5	19.3	25.4
160	3.09	2.44	2.87	1000	32.0	21.9	28.6
170	3.40	2.88	3.16	1100	35.4	24.5	31.8
180	3.72	2.93	3.46	1200	38.9	27.3	35.0
190	4.04	3.17	3.75	1300	42.4	30.1	38.3
200	4.35	3.41	4.04	1400	45.9	33.0	41.6
210	4.67	3.65	4.33	1500	49.3	36.0	44.9
220	4.99	3.89	4.62	1600	52.8	39.1	48.2

Table III Average Intrinsic Electrical Resistivity of Ruthenium (1600 K to 2606 K)

Temperature, K	$\rho_{i\,avr}$, µΩ cm	Temperature, K	$\rho_{i\,avr}$, µΩ cm
1600	48.2	2200	67.5
1700	51.4	2300	70.8
1800	54.5	2400	74.1
1900	57.7	2500	77.5
2000	61.0	2600	80.9
2100	64.2	2606	81.1

and Brunen and Milošević up to 2500 K are shown in **Figure 1**.

Osmium

Selected resistivity values at 273.15 K are given in **Table IV**. As with ruthenium, because of the possibility of preferred orientation in polycrystalline samples only results for single crystals are considered in this selection. Values given by Powell *et al.* (11) were corrected for residual resistivity based on the ratio $\rho_{273\,K}$ / $\rho_{4.2\,K}$ = 33.3 given as a private communication to Ho *et al.* (21). The selected values in **Table IV** are based on the values of Volkenshtein (22) since they were precision determinations on high purity material at 273.15 K.

Schriempf (23) (2–20 K) determined the anisotropic resistivities at 60° and 16° to the *c* axis but did not give values of $\rho_i \perp$ and $\rho_i \parallel$. The average values of White and Woods (6, 7) (25–295 K) were corrected to conform to the selected value at 273.15 K using the ratio 8.07/8.35 and at 80 K and above fitted to Equation (xi)

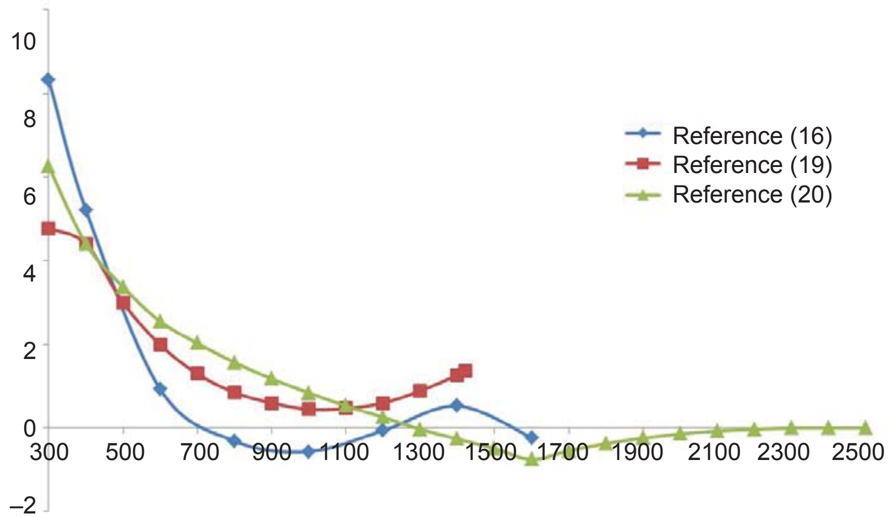

Fig. 1. Solid ruthenium – percentage deviations from selected curve

Table IV Electrical Resistivity of Osmium at 273.15 K

Authors	Ref.	ρ_i ⊥, μΩ cm	ρ_i ǁ, μΩ cm	$\rho_{i\ avr}$, μΩ cm	Temperature of data
White and Woods	6, 7	–	–	8.35	At 273.15 K
Powell *et al.*	8	–	–	8.26	At 273.15 K. As received sample corrected for ρ_0 0.27 μΩ cm
		–	–	7.88	At 273.15 K. Sample annealed at 1813 K corrected for ρ_0 0.24 μΩ cm
Powell *et al.*	11	–	–	7.85	Interpolated 200–400 K. Corrected for ρ_0 0.24 μΩ cm
Volkenshteyn	22	9.346	5.532	8.075	At 273.15 K
Selected		**9.35**	**5.53**	**8.07**	**At 273.15 K**

with an overall accuracy as a standard deviation of ±0.02 μΩ cm. Values were only given at 30 K and above because of the possibility of unaccounted for residual resistivity.

In the high temperature region anisotropic resistivity measurements of Savitskii *et al.* (24) (300–1600 K) were only shown graphically with actual data points given by Savitskii *et al.* (17). These only show satisfactory agreement with the selected values at 600 K and above for the axis perpendicular to the *c* axis and 1000 K and above for the axis parallel to the *c* axis and therefore lower temperature measurements were rejected in each case. The values were corrected for thermal expansion using the length values selected by the present author (25). However these extended only to 1300 K and values above this temperature were obtained by extrapolation. The corrected values were then fitted to Equations (xii) to (xiv) which were used to represent the thermal expansion from 273.15 K to 1600 K with overall accuracies as standard deviations of ±0.40 μΩ cm and ±0.51 μΩ cm respectively. Percentage deviations of the measurements of Savitskii *et al.* from the selected values are shown in **Figure 2** whilst selected values of intrinsic electrical resistivity for osmium are given in **Table V**.

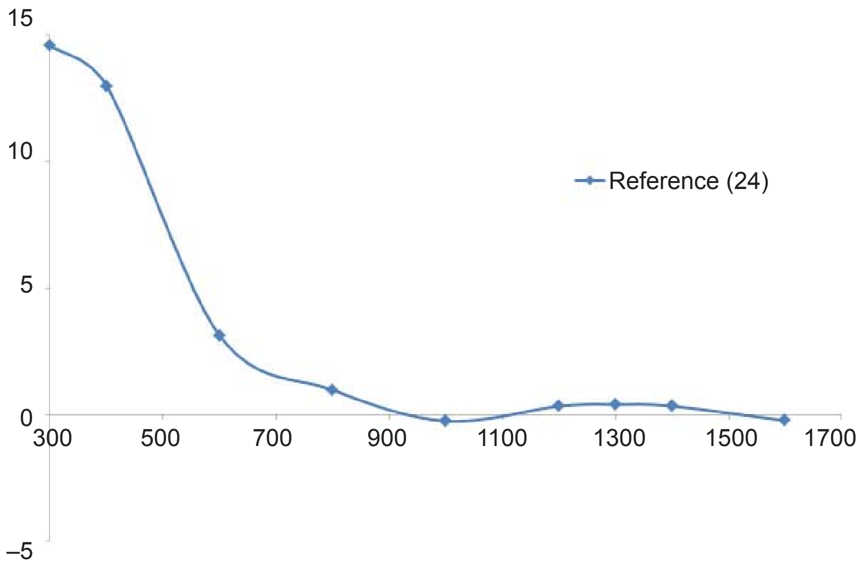

Fig. 2. Solid osmium – percentage deviations from selected curve

Table V Intrinsic Electrical Resistivity of Osmium

Temperature, K	$\rho_{i\ avr}$, µΩ cm	Temperature, K	$\rho_i \perp$, µΩ cm	$\rho_i \parallel$, µΩ cm	$\rho_{i\ avr}$, µΩ cm
30	0.027	240	–	–	6.92
40	0.11	250	–	–	7.26
50	0.25	260	–	–	7.61
60	0.48	270	–	–	7.76
70	0.76	273.15	9.35	5.53	8.07
80	1.05	280	9.70	5.73	8.38
90	1.45	290	10.2	6.03	8.82
100	1.85	300	10.7	6.32	9.25
110	2.23	400	15.7	9.27	13.6
120	2.62	500	20.6	12.2	17.8
130	2.99	600	25.4	15.1	22.0
140	3.36	700	30.0	18.1	26.0
150	3.73	800	34.5	21.0	30.0
160	4.10	900	39.0	23.9	33.9
170	4.46	1000	43.2	26.8	37.8
180	4.81	1100	47.4	29.7	41.5
190	5.17	1200	51.5	32.6	45.2
200	5.52	1300	55.4	35.5	48.8
210	5.87	1400	59.2	38.4	52.3
220	6.22	1500	62.9	41.3	55.7
230	6.57	1600	66.5	44.2	59.1

Anisotropic measurements of Schriempf (23) at 297 K differs significantly from the selected value perpendicular to the *c* axis being 0.98 µΩ cm low whilst the value along the *c* axis is 0.15 µΩ cm high. The corrected average value of Powell *et al.* (11) at 500 K is 15% low whilst average values of L'vov *et al.* (26) (100–1700 K) over the mutual high temperature range 500 K to 1300 K average 22% low. Average measurements of Gugnin *et al.* (27) (373–1973 K) were only shown in the form of small graphs.

Low Temperature Intrinsic Resistivity of Ruthenium Below 30 K

$$\rho_{i\perp}\ (\mu\Omega\ \text{cm}) = 2.8 \times 10^{-6}\ T^{2} + 2.8 \times 10^{-10}\ T^{5}\ \mu\Omega\ \text{cm} \quad \text{(i)}$$

$$\rho_{i\parallel}\ (\mu\Omega\ \text{cm}) = 2.3 \times 10^{-6}\ T^{2} + 2.4 \times 10^{-10}\ T^{5}\ \mu\Omega\ \text{cm} \quad \text{(ii)}$$

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 2.6 \times 10^{-6}\ T^{2} + 2.7 \times 10^{-10}\ T^{5}\ \mu\Omega\ \text{cm} \quad \text{(iii)}$$

Low Temperature Intrinsic Resistivity of Ruthenium (100 to 273.15 K)

$$\rho_{i\perp}\ (\mu\Omega\ \text{cm}) = 3.13425 \times 10^{-2}\ T + 7.13667 \times 10^{-7}\ T^{2} - 1.94445 \quad \text{(iv)}$$

$$\rho_{i\parallel}\ (\mu\Omega\ \text{cm}) = 2.57537 \times 10^{-2}\ T - 4.37527 \times 10^{-6}\ T^{2} - 1.56817 \quad \text{(v)}$$

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 2.94796 \times 10^{-2}\ T - 9.82645 \times 10^{-7}\ T^{2} - 1.81902 \quad \text{(vi)}$$

High Temperature Intrinsic Resistivity of Ruthenium (273.15 to 1600 K)

$$\rho_{i\perp}\ (\mu\Omega\ \text{cm}) = 3.48448 \times 10^{-2}\ T - 3.42085 \times 10^{-8}\ T^{2} - 2.84530 \quad \text{(vii)}$$

$$\rho_{i\parallel}\ (\mu\Omega\ \text{cm}) = 1.77020 \times 10^{-2}\ T + 4.20211 \times 10^{-6}\ T^{2} - 8.82460 \times 10^{-3} \quad \text{(viii)}$$

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 2.91305 \times 10^{-2}\ T + 1.37790 \times 10^{-6}\ T^{2} - 1.89981 \quad \text{(ix)}$$

High Temperature Intrinsic Resistivity of Ruthenium (1600 to 2606 K)

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 2.68820 \times 10^{-2}\ T + 1.37576 \times 10^{-6}\ T^{2} + 1.70317 \quad \text{(x)}$$

Low Temperature Intrinsic Resistivity of Osmium (80 to 273.15 K)

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 4.68970 \times 10^{-2}\ T - 4.94870 \times 10^{-5}\ T^{2} + 6.71192 \times 10^{-5}\ T^{3} - 2.41554 \quad \text{(xi)}$$

High Temperature Intrinsic Resistivity of Osmium (273.15 to 1600 K)

$$\rho_{i\perp}\ (\mu\Omega\ \text{cm}) = 5.41521 \times 10^{-2}\ T - 5.90401 \times 10^{-6}\ T^{2} - 5.00114 \quad \text{(xii)}$$

$$\rho_{i\parallel}\ (\mu\Omega\ \text{cm}) = 2.96326 \times 10^{-2}\ T - 2.67298 \times 10^{-7}\ T^{2} - 2.54420 \quad \text{(xiii)}$$

$$\rho_{i\ avr}\ (\mu\Omega\ \text{cm}) = 4.59789 \times 10^{-2}\ T - 4.02511 \times 10^{-6}\ T^{2} - 4.18216 \quad \text{(xiv)}$$

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