Magneto-resistance Effect and Electric Resistance of Single Crystals of Cobalt*

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(Received May 18, 1966)

Synopsis

The preparation of long bar specimens of single crystals of close-packed hexagonal cobalt, about 10 cm long, was succeeded for the first time by the present authors, and with these crystals, the anisotropy of electrical resistivity and the magneto-resistance effect were measured up to the field of 1000 Oe. It was found that the specific electrical resistivity was largest in the direction of c-axis and smallest in the direction perpendicular to the axis, being $10.280\times10^{-6}\Omega$-cm and $5.544\times10^{-6}\Omega$-cm, respectively, and the values of $\Delta R/R$ were about 0.4 per cent and about 0.2 per cent the respective directions.

I. Introduction

Whereas a number of research(1) have dealt with the electrical resistivity of poly-crystals of close-packed hexagonal cobalt, no report is available on the single crystal of cobalt owing to the difficulties in the preparation of the crystal sufficiently long to measure the resistivity. In the present investigation, therefore, an attempt was made of producing long single crystals of cobalt by Tammann-Bridgman's method(2) and long bars of single crystals of cobalt, about 10 cm long, could be obtained by controlling the cooling rate. The anisotropy of electrical resistivity in the specimens of single crystals of cobalt with various axial directions was then measured.

In regard to the magneto-resistance effect, there is only one report by Shirakawa(3) on poly-crystals of cobalt. In the present case the longitudinal magneto-resistance effect was also measured with the single crystals mentioned above. At the same time the electrical resistivities in the direction of c-axis, $\rho_{\parallel}$, in the perpendicular direction to the c-axis, $\rho_{\perp}$, and in a given direction, ρ_{φ}, were calculated from the results of resistivity measurements of some specimens by the least square method.

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* The **1246th** report of the Research Institute for Iron, Steel and Other Metals, and the **4th** report of the Foundation: The Research Institute of Electric and Magnetic Alloys.

** The Foundation: The Research Institute of Electric and Magnetic Alloys.

(1) H.T. Kalmus and C. Harper, *The Physical Properties of the Metal Cobalt*, 1914, Gov. Printing Bur. Ottawa: *Int. Critical Table*, 1926, Vol. 1, 103; 104: *Metals Handbook*, 1954, Suppl. A.S.M. N.Y.: *Rikagaku-Jiten*, 1965, Iwanami, Tokyo.

(2) M. Yamamoto, Sci. Rep. Tôhoku Imp. Univ., **29** (1940), 113: J. Japan Inst. Met., **4** (1940), 368.

(3) Y. Shirakawa, Sci. Rep. Tôhoku Imp. Univ., Honda Aniv. Vol. (1936), 362; **27** (1939), 532.

II. Single crystal specimens and method of measurement

1. Single crystal specimens

To prepare the single crystals, an electrolytic cobalt was melted and cast into an iron mould, 30 cm in length and 10 mm in diameter, in vacuo. The ingot was swaged at high temperatures to a wire, 2 mm in diameter. The wires in proper length were cut off from it to be used as the material of single crystals. The results of chemical analysis of electrolytic cobalt used are given in Table 1.

Table 1. Chemical analysis of electrolytic cobalt.

Elements	Fe	Ni	Al	C	Si	Mn	P	S
%	0.120	0.010	0.033	0.028	0.012	0.001	0.002	0.006

It has so far been considered that the preparation of long single crystals of cobalt by Tammann-Bridgman's method is extremely difficult, because of the $\varepsilon \rightleftarrows \gamma$ transformation known as Masumoto's transformation⁽⁴⁾. In the present case, the preparation of such single crystals could be succeeded by slow cooling in the temperature range near the transformation point: The optimum descending velocity of the crucible (2 mm in inner diameter) to obtain the single crystals having an axial direction parallel to the c-axis was below about 0.1 mm/min, and that for the crystals perpendicular to the c-axis was about 0.1 to 0.2 mm/min.

It was found that in the case of cobalt, the easily obtainable direction was perpendicular to the c-axis contrary to other hexagonal crystals⁽⁵⁾. But, the crystals having a given direction must be chosen from a number of the crystals prepared by the above-mentioned method, because unlike nickel single crystals it was difficult to obtain a proper crystal. The bar specimens, about 6 to 11 cm in length and about 2 mm in diameter, were cut from the selected single crystals by means of etching with nitric acid to avoid the introduction of residual stress. The cut surface of the specimens was carefully polished with emery paper of the 0/5 grade and finally polished electrolytically.

The axial direction of the specimens was determined by the light figure method⁽⁶⁾ after etching in the boiled saturated solution of ferric chloride.

All the specimens were heated in vacuo to remove the residual stress for about 10 hr at 350°C which is fairly lower than the transformation point, and again polished electrolytically. Fig. 1 shows the stereographic projection⁽⁷⁾ of the orientation of the axial direction of all the specimens. The numbered specimens in the figure were used for the measurement, and the inclinations of their axial directions to the c-axis are given in Table 2 with their dimensions.

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(4) H. Masumoto, Kinzoku-no-Kenkyû, **2** (1925), 877.

(5) M. Yamamoto, J. Japan Inst. Met., **4** (1940), 27; 168; 222.

(6) M. Yamamoto, J. Japan Inst. Met., **4** (1940), 368; **5** (1941), 214; J. Appl. Phys., Japan, **10** (1940), 199.

(7) M. Yamamoto, Met. Phys., **6** (1960), 118.

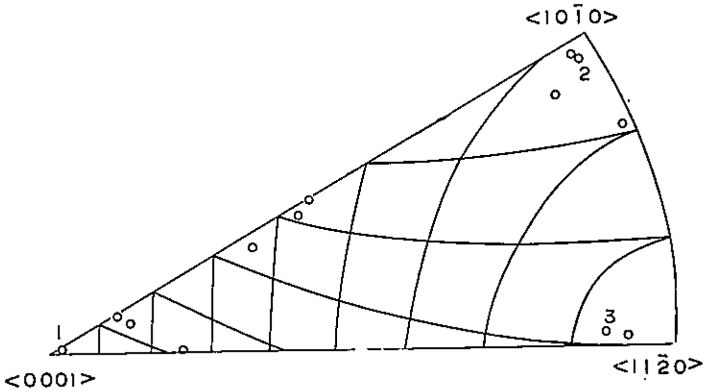

Fig. 1. Stereographic projection of orientations of the single crystals of cobalt.

Table 2. Dimensions and orientations of single crystal specimens of cobalt used.

Specimen No.	Dimensions (cm)		Direction (cosine)			
	Length	Diameter	α	β	γ	θ
1	7.417	0.1821	89.9	88.5	92.5	2.06
2	6.567	0.1799	30.3	32.0	151.5	84.20
3	10.043	0.1783	26.4	59.0	173.0	82.80
Poly-crystal	9.970	0.1949	—	—	—	—

2. Method of measurement

The electrical resistivity was measured by the potentiometric method, and the magnetization by a galvanometer method at room temperature. As the demagnetization factor, the values proposed by Schuddemagen(8) were used.

III. Results

The results of measurements are shown in Figs. 2~5. In the figures, the abscissa represents the effective field, H, in Oe, and the ordinate the relative changes in electric resistance, $\Delta R/R$, and in magnetization, I/I_S. As the saturation value of magnetization, the results obtained previously by one of the present authors(9) was used. Fig. 2 shows the results of measurements with the specimen having the axial direction near ⟨0001⟩. As seen in the figure, the change in $\Delta R/R$ under the application of the field was almost similar to that of magnetization, that is, $\Delta R/R$ increased at first rapidly with the increase of the field, and above about 200 Oe the increasing rate became slow and reached its saturation value. The specific electrical resistivity, ρ, was $10.280\times10^{-6}\Omega$-cm with no field, and $10.320\times10^{-6}\Omega$-cm at the field of 1000 Oe, the saturation value of $\Delta R/R$ being about 0.4 per cent.

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(8) C.L.B. Schuddemagen, Phys. Rev., **31** (1910), 165.

(9) K. Honda and H. Masumoto, Sci. Rep. Tôhoku Imp. Univ., **20** (1931), 323.

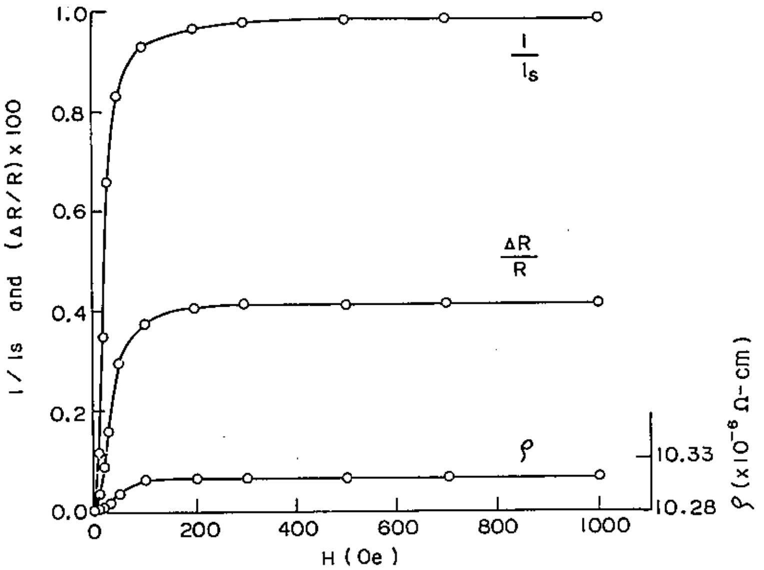

Fig. 2. Magneto-resistance, specific electrical resistivity and magnetization curves of the single crystal of cobalt having the axial direction near ⟨0001⟩ (Specimen No. 1).

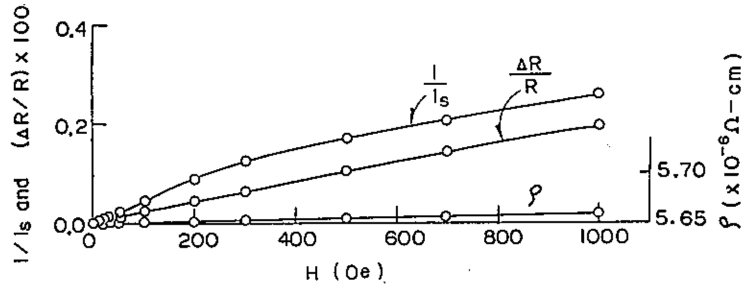

Fig. 3. Magneto-resistance, specific electrical resistivity and magnetization curves of the single crystal of cobalt having the axial direction near ⟨10$\bar{1}$0⟩ (Specimen No. 2).

In Fig. 3 are given the results obtained with the specimen in the axial direction near ⟨10$\bar{1}$0⟩, in which the changes in $\Delta R/R$ and I with the field show similarly a linear relationship with the field; ρ at $H=0$ is $5.645\times10^{-6}\Omega$-cm, at $H=1000$ Oe $5.656\times10^{-6}\Omega$-cm, and the $\Delta R/R$ about 0.18 per cent. The magnetization in this axial direction does not reach its saturation value until the field of 10,000 Oe(9), nor does $\Delta R/R$.

In the axial direction near ⟨11$\bar{2}$0⟩, the changes in $\Delta R/R$ and I are almost similar to those in the ⟨10$\bar{1}$0⟩ direction as seen in Fig. 4; ρ changes from $5.544\times10^{-6}\Omega$-cm at $H=0$ to $5.553\times10^{-6}\Omega$-cm at $H=1000$ Oe, and $\Delta R/R$ being about 0.2 per cent.

The value of $\rho_{/\!/<0001>}/\rho_{\perp<0001>}$ obtained from the preceding results was 1.82 with no field.

Fig. 5 shows the results obtained with the specimen of poly-crystal of cobalt.

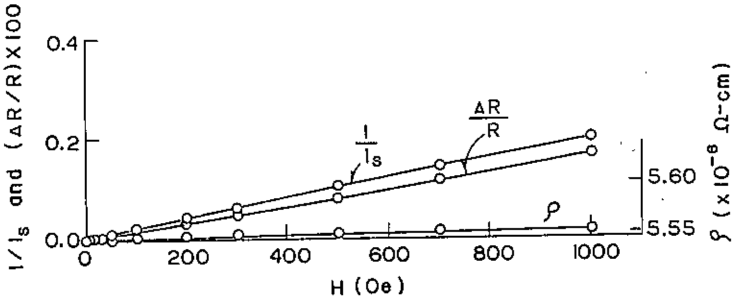

Fig. 4. Magneto-resistance, specific electrical resistivity and magnetization curves of the single crystal of cobalt having the axial direction near ⟨11$\bar{2}$0⟩ (Specimen No. 3).

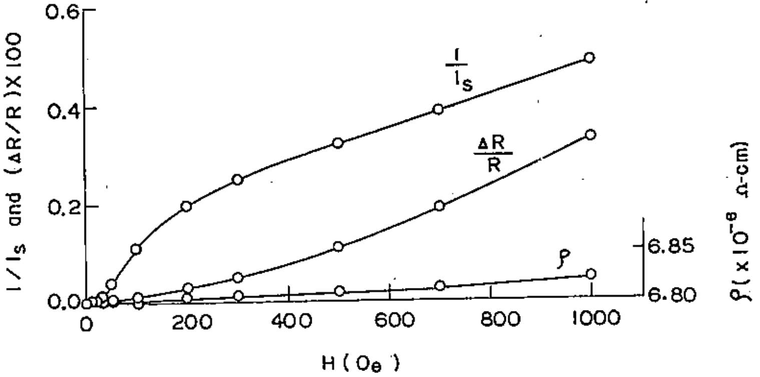

Fig. 5. Magneto-resistance, specific electrical resistivity and magnetization curves of a poly-crystalline cobalt.

As seen in the figure, $\Delta R/R$ and I do not show a parallel correlation to the field, different from the case of single crystals mentioned above. In the poly-crystal specimen, the increasing rate of $\Delta R/R$ due to the field is at first very slow, and then becomes fairly fast above the field of about 300 Oe; ρ changes from $6.85\times10^{-6}\Omega$-cm at $H=0$ to $6.87\times10^{-6}\Omega$-cm at $H=1000$ Oe, $\Delta R/R$ reaching about 0.33 per cent. These values can be regarded as reasonable in comparison with those of other workers which ranged from $5.5\times10^{-6}\Omega$-cm to $9.7\times10^{-6}\Omega$-cm at room temperature⁽¹⁾, and also the results of $\Delta R/R$ is almost similar to that obtained by Shirakawa⁽³⁾ at room temperature.

In Fig. 6 is shown the specific electrical resistivity in a given direction, ρ_φ, calculated from the equation

$$\rho_\varphi = \rho_\perp + (\rho_{/\!/} - \rho_\perp)\cos^2\varphi\ . \tag{1}$$

As seen in the figure, ρ_φ changes slowly and monotonously from the maximum value in the direction of the c-axis to the minimum value in the direction perpendicular to the axis with no field. The same relation is maintained even at the field of 1000 Oe, except that the value is fairly large in the latter.

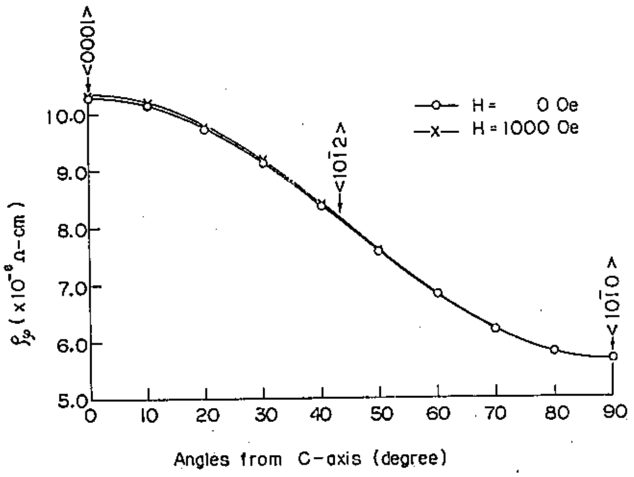

Fig. 6. Relation between axial direction of single crystals of cobalt and specific electrical resistivity.

Summary

The magneto-resistance effect, $\Delta R/R$, has been measured with long single crystals of close-packed hexagonal cobalt at the field up to 1000 Oe, and the following results were obtained.

(1) In the axial direction of ⟨0001⟩, $\Delta R/R$ increases rapidly up to the field of about 200 Oe and reaches a saturation value of about 0.4 per cent; ρ is $10.280\times 10^{-6}\Omega$-cm at $H=0$ and $10.320\times10^{-6}\Omega$-cm at $H=1000$ Oe.

(2) In the direction of ⟨10$\bar{1}$0⟩, $\Delta R/R$ increases almost linearly without reaching its saturation value; ρ changes from $5.645\times10^{-6}\Omega$-cm at $H=0$ to 5.656×10^{-6} Ω-cm at $H=1000$ Oe, and $\Delta R/R$ is about 0.18 per cent.

(3) In the ⟨11$\bar{2}$0⟩ direction, $\Delta R/R$ increases almost linearly to about 0.2 per cent; that is, ρ increases from $5.544\times10^{-6}\Omega$-cm at $H=0$ to $5.553\times10^{-6}\Omega$-cm at 1000 Oe.

(4) In the poly-crystal, $\Delta R/R$ increases in the way similar to the single crystals having the axial direction perpendicular to the c-axis but the increasing rate is somewhat larger than the latter; ρ changes from $6.85\times10^{-6}\Omega$-cm to $6.87\times10^{-6}\Omega$ -cm, and $\Delta R/R$ is about 0.3 per cent.

(5) With no field, $\rho_{/\!/<0001>}/\rho_{\perp<0001>}$ is about 1.8.

Acknowledgement

The present authors wish to express their appreciation to Dr. J. Watanabé and Mr. S. Kadowaki for their kind assistance in the preparation of the single crystal specimens.