EFFECT OF MAGNETIC FIELDS UPON THERMAL CONDUCTIVITY OF IRON, COPPER, GOLD, SILVER AND ZINC

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Abstract

A "bar method" was used to measure *thermal conductivity* and *electrical resistivity* for iron, copper, gold, silver and zinc in and out of a longitudinal field of 10,000 gauss, and transverse fields of 8,000 and 4,000 gauss. Copper-constantan thermo-couples "spot" welded to the bars were used to measure the temperatures. For iron, the 10,000 gauss longitudinal field caused a 1.14 percent decrease in heat conductivity and the transverse field of 4,000 gauss caused a 0.4 percent decrease. Electrical resistivity was increased 0.2 percent by the 10,000 gauss field. For copper, the thermal conductivity was decreased 0.23 percent by the 10,000 gauss field. In all the other cases the fields were shown to produce no effects large enough to detect, although the method would readily show any change as great as 0.04 percent. Zinc was used in the ordinary cast form, and in the slowly grown crystal bars. The values of electrical and thermal conductivity were higher in the crystal bar, but the magnetic fields produced no change in either bar. Thus, contrary to theories of Livens and others, these metals failed to show an increase in thermal conductivity in strong fields.

Introduction

THE effect of magnetic fields upon the thermal conductivity of metals has been investigated most fully for the ferro-magnetic elements iron and nickel. Considerable work has been done with bismuth and tellurium. The thermal conductivity of these metals seems to be decreased by magnetic fields. Livens[1] however, starting with the free electron theory arrives theoretically at the conclusion that all metals should show an increase in thermal conductivity in a magnetic field. He believes that in the ferromagnetic metals, the internal field may reverse the sign of the effect, as may also be the case for bismuth and tellurium. In this research, the effect of the magnetic field upon thermal conductivity is measured for iron, copper, gold, silver and zinc.

Experimental Methods and Apparatus

A "bar method" is used to measure the thermal conductivity. The magnitude of the thermal conductivity is given in terms of the temperatures at two points on the bar. Any slight changes in these temperatures due to the magnetic field may therefore be interpreted as a change of thermal conductivity.

O'Day[2] shows that when a current flows through a bar, cooled at the ends and radiating to a boundary at the same temperature, the equation of heat conduction takes the form:

[1] Livens, Phil. Mag. **30,** 526 (1915).
[2] O'Day, Phys. Rev. **23,** 245 (1924).

$$A\frac{d}{dx}\left(K\frac{d\theta}{dx}\right)-Is\frac{d\theta}{dx}+\left(\frac{I^2R_0\alpha}{J}-h\right)\theta=-\frac{I^2R_0}{J}$$

where θ is the temperature in degrees centigrade at any point on the bar relative to the temperature of the ends; A the cross section of the bar; $K=K_0(1-\beta\theta)$ the heat conductivity of the metal; $R=R_0(1+\alpha\theta)$ the resistance of the bar; I the current; s the coefficient of the Thomson effect; J the mechanical equivalent of heat in joules per calorie; h the radiation per cm of the bar. In this equation the change in thermal and electrical conductivity with temperature, its loss of heat by radiation, and the Thomson effect are taken into account. When the temperature distribution for the steady state is parabolic in the length of the bar, the value of the thermal conductivity is

$$K_0=R_0L^2I^2/2JA\theta_m$$

where K_0 is the heat conductivity of the metal at the temperature of the ends of the bar; R_0 the resistance of the bar at end temperature; L one-half the length of the bar; I the current giving the parabolic distribution of temperature and θ_m the temperature of the middle of the bar, referred to the ends as zero.

To obtain the value of the current to produce parabolic distribution, O'Day used the relation $\theta_m\equiv\frac{1}{2}Lp_0$ where p_0 is the temperature gradient at the end of the bar as measured by means of two thermocouples, one at the end of the bar, and one near the end. If the bar is long, the gradient may be obtained accurately in this manner, but if the bar is short, the temperature gradient is not even approximately linear, even for a short distance from the ends of the bar. To place bars longitudinally in a strong magnetic field necessarily limits the length of the bar and we have therefore in the present investigation had recourse to the following method of obtaining the value of the current necessary to produce parabolic temperature distribution.

One couple is placed at the end, one half-way to the middle, and one at the middle of the bar. When the temperature distribution is parabolic, the ratio of the temperature at the middle point to that at the second point is a constant for any form of parabolic distribution having zero temperature at the end points. The ideal value of this constant is computed. Then, as in O'Day's work, various currents are tried, and the one giving the correct ratio is used. For this current we have correct distribution, and the formula for heat conductivity is applicable.

To measure the Thomson effect O'Day used couples at 0.42 L from each end. These can also well be used to obtain the value of the current for parabolic temperature distribution. The couples near the ends can then be dispensed with, leaving five couples instead of seven, to accomplish all measurements.

The method of attaching the couples to the bar is of importance. In this work, two methods are used. First, for the metals of low melting point the bars are cast in a special iron mold, which holds the five thermocouple wires so that the ends barely enter the metal. When the casting cools, the wires are held tightly. Copper and constantan wires No. 36 B. S. gauge are used and the wires of each couple enter the metal 0.8 mm on diametrically opposite sides of the bar. The bars being approximately 3 mm in diameter, the cross section is altered very little. It is seen then, that the couple circuit is closed by the bar itself, which is therefore the intermediate metal, but it is believed that no inconsistency is introduced by this feature. When direct current is used to heat the bar, there may be a slight *IR* drop between the two sides of the couple, but the true temperature is given by the average of the readings obtained with the current, first in one and then in the reverse direction.

A second method is used for metals of higher melting point. The couple wires of copper and constantan are "spot" welded on opposite sides of the bar. The bar is first marked with fine knife lines on opposite sides and exactly even in the longitudinal direction. The bars are then welded on the fine knife lines. In this manner, the cross section of the bar is scarcely altered, and the couple will give the temperature exactly at the surface of the bar. This method is used on the metals here discussed and seems to be an excellent method of attaching couples where insulation of the couple is not required.

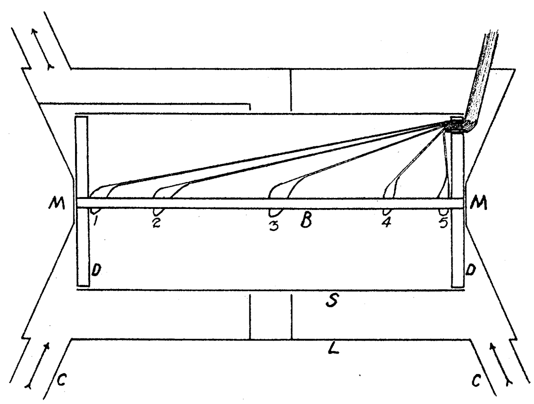

Fig. 1. Diagram of apparatus.

It is assumed in the derivation of Eq. (1) that the ends of the bar are at some definite temperature, which is the same as that of the region to which the bar radiates heat. To realize this condition the ends of the bar *B* (Fig. 1) are fitted into copper disks *D*, 5 cm in diameter and 3 mm thick. The bar fits rather tightly in each disk. The hole in the disk, and the end of the bar are tinned with solder, and then the disk is "sweated" onto the bar. This method gives a very good electrical and thermal contact between the bar and the disks. Around each disk a wide rubber band is stretched, and cemented with shellac. Over the whole is slipped a brass sheath *S*, forming an air-tight chamber around the bar. The length of the bar is 10 cm between the extreme couples which are 0.5 mm inside the end disks. The couple leads are carried through the end plates by a small rubber tube. The bar is heated by current from connections to the end plates. Heat radiates through the air space from the bar to the walls of the chamber. The temperature of the whole sample chamber is kept constant by rapidly circulating ice water around it inside a second chamber L. The stream of ice water is taken from the bottom of a large box containing crushed ice and water, and directed through two connections CC to the ends of the sample chamber. A distributing valve is arranged to regulate the flow to each end in proper proportion to keep the two ends at the same temperature when heat is generated in the bar by the heating current. The water returns from each end of the bar along the brass sheath to an annular channel which leads entirely around the chamber, and is carried back to the top of the ice box, again to trickle down through the ice. By this means, the temperatures of the ends are held constant and equal, within a variation of 0.0025°C.

The other junctions of the couples are immersed in mercury in capillary tubes placed in a Dewar flask filled with shaved ice. A set of double-pole switches is arranged to connect any couple to a pair of bus wires leading to the galvanometer and a White double potentiometer (four-dial 10,000 microvolt range). The double potentiometer enables one to measure the temperature of any two different couples almost simultaneously. The galvanometer is of the D'Arsonval type, sufficiently sensitive to give 5 mm deflection per micro volt on a scale three meters distant. Whole microvolts are read on the potentiometer dials, always leaving less than one microvolt to be read on the scale.

To furnish the magnetic field, a magnet and auxilliary coil to obtain a field of 10,000 gauss across a 10.7 cm gap is used. The magnet gives almost 5,000 gauss in the middle of the gap, and of course the field is much stronger at the pole tips. The pole tips fit into the conical cups MM (Fig. 1). The ends of the water jacket are of thin copper, so that the tips of the poles come very close to the ends of the bar. A thin layer of asbestos is placed between the copper ends and the poles for thermal insulation. The field in the middle of the gap is strengthened by means of a 90 turn oil-cooled solenoid around the gap which carries a current of 800 amperes furnished by a motor-generator set. The field produced by both the magnet and the solenoid is 10,000 gauss in the middle of the gap, and slightly more near the pole tips. This field may be maintained continuously, thus allowing ample time for all measurements. The transverse field is obtained with the magnet alone, using wedge shaped tips and a 5 cm gap. The maximum field strength is then 8,000 gauss.

Measurements

A set of data consists of measurements on the following: half-length of the bar, L; cross section of the bar, A; resistance per centimeter of the bar, R; thermal e.m.f. of the couples; current, I, necessary to secure parabolic temperature distribution; temperature θ_m at middle of the bar with respect to the ends. Then as was shown above, the thermal conductivity of the sample can be computed in terms of these values from Eq. (1). The measurement of length is made by means of the vernier scale used to space the couples. The length of the bar is considered to be the distance between the end couples. This distance is made 10 centimeters on all the bars investigated. The half-length L is then 5 centimeters. The cross section is measured in two ways: (a) the diameter is measured with micrometer calipers at many places on the bar, and the cross section computed; (b) a length of bar usually greater than that mounted, is weighed and the cross section computed, using best tabular values of the density for the pure metal. The average cross section given by the two methods is the one used in the computation. In the case of zinc, the density was determined experimentally. The resistance of the bar is determined by measuring the potential drop between copper sides of the different couples when a known current flows in the bar. The current is measured almost simultaneously with the same potentiometer by the drop over a standard 0.0001 ohm resistance. Error of spacing the couples along the bar are averaged out by taking the potential drop over all possible combinations. The average error of spacing was not usually more than 0.1 percent.

The thermal e.m.f. of the couples is measured by circulating water of various temperatures around the sample chamber, while the Dewar flask is filled with shaved ice. The constant for the welded couples never varies more than one microvolt in 1000 among different couples, even on bars of different metals. Concerning the absolute value of the constant, the junctions in the Dewar flask are assumed to be at zero degrees centigrade, and the temperature of the water bath is measured with a Haak thermometer graduated in tenths of degrees from 0 to 50°C.

A second bar is grown in a single crystal inside a glass tube. The metal is slowly cooled from the lower end upward at the rate of 2 cm per hour. Such bars, when broken, break at any point with the planes of the ends parallel. In the case of zinc, the bar grown in this manner has an elliptical cross section even though coolel in a round tube. The method is believed to have been first used by Professor A. F. Joffé, and at his suggestion the single crystal is used in this work. The cleavage plane of the bar used is inclined approximately 70° to the axis of the crystal.

Except for iron, alternating current is used for heating the bar. In the case of iron, the skin effect made it necessary to use direct current.

The values in the absence of a magnetic field of the specific electrical resistance ρ and heat conductivity K for all the metals investigated are presented in Table I.

TABLE I. *Values of specific resistance ρ and thermal conductivity K in the absence of a magnetic field.*

Metal	A cm^2	L cm	I amp	θ_m °C	R (ohm/cm) $\times 10^6$	ρ (ohm/cm) $\times 10^6$	K_0 (cals/cm^2 °C)
Iron	.0794	5	35	38.92	151.3	11.99	0.179
Copper	.0510	5	60	6.523	30.84	1.575	0.994
Silver	.0783	5	100	6.751	19.06	1.492	1.08
Gold	.0779	5	75	8.471	28.50	2.219	0.726
Zinc	.0861	5	70	39.55	65.26	5.622	0.281
Zinc*	.0807	5	50	20.00	67.83	5.474	0.303

* Single crystal bar.

Though the purpose in this research is not to measure ρ and K_0 with exceptional accuracy, it is believed that the values on the resistivity ρ are accurate to at least 0.5 percent, and those on thermal conductivity K_0 to 1.0 percent. It is noted that the values of electrical and thermal conductivity for the single crystal of zinc are higher than for the ordinary bar. Griffiths[3] has recently shown that the heat conductivity of single crystal aluminum is the same as for cast aluminum. However, this does not indicate that zinc would act the same way, for zinc crystals are of a different system from those of aluminum.

The changes in ρ and K_0 due to the magnetic fields are given in the Table II. In each case the ratio of the value in the field to that with no field is given:

TABLE II. *Changes in ρ and K produced by the application of a magnetic field.*

Metal	Longitudinal Field 10,000 gauss‡		Transverse Fields 8,000 gauss		Transverse Fields 4,000 gauss	
	ρ'/ρ	K'/K	ρ'/ρ	K'/K	ρ'/ρ	K'/K
Iron†	1.0020	0.9886	1.0000	1.000	1.0000	0.996
Copper	1.0004	0.9977	1.0000	1.000	1.0000	1.000
Silver	1.0000	1.000	1.0000	1.000	1.0000	1.000
Gold	1.0000	1.000	1.0000	1.000	1.0000	1.000
Zinc	1.0000	1.000	1.0000	1.000	—	—
Zinc*	1.0000	1.000	1.0000	1.000	—	—

* Single crystal bar.

† The 10,000 gauss field gives 36,000 lines of induction measured by means of a fluxometer and a coil of very fine wire wrapped tightly around the bar.

‡ An 8,000 gauss longitudinal field produces a 0.21 per cent decrease in K_0 for copper.

Discussion of Results

The precision and consistency of observations on the effect of the field are sufficient readily to detect a change in ρ as small as 0.02 percent, and in K_0 as small as 0.04 percent. Of the four non-magnetic metals, copper, silver, gold and zinc, only copper shows an appreciable change in heat conductivity. This change, a decrease of 0.23 percent in the longitudinal field, was verified with several different values of heating current, and with two field strengths. Loosening the magnetic poles does not affect the results, thus precluding any possibility of the change being caused by heat from the magnet, which becomes only slightly warm. For that matter, changing the temperature of the water bath does not appreciably change the results. Thus, if seems that the results for copper are contrary to Livens' theory, as has been the case for magnetic metals. Gold, silver, and zinc show no change in either electrical or thermal conductivity as much as 0.04 percent. It may be remarked that Little[4] has recently found arsenic to show no change in thermal or electrical conductivity with a magnetic field.

It is interesting that the 4,000 gauss transverse field changes the heat conductivity of iron 0.4 percent, while the 8,000 gauss field produces no

[3] Griffiths Roy. Soc. Proc. A **115**, 236 (1926).

[4] Little, Phys. Rev. **28**, 418 (1926).

change as great as 0.04 percent. Grunmach and Weidert[5] report that they found the resistance of iron first to increase with field strength and then to decrease having no change at 10,000 gauss. It appears possible that this behavior is paralleled in the case of heat conductivity.

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[5] Grunmach and Weidert, Phys. Zeits. **7**, 729 (1906).
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