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THERMAL CONDUCTIVITY OF SOME IRONS AND STEELS OVER THE TEMPERATURE RANGE 100 TO 500 C

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ABSTRACT

The thermal conductivities over the temperature range 100 to 500 C have been determined for 20 irons and steels which were selected as typical examples of commercial materials used for a variety of purposes and expected to have considerably different thermal conductivities. The data on the chromium-iron and chromium-nickel-iron alloys are of particular interest because of the lack of previous data on the thermal conductivity of "stainless" steels.

The apparatus was designed for comparative measurements and thus eliminated calorimetric or power-input determinations which are difficult to perform with uniformly high accuracy over a broad range of temperature. High-purity lead was used, either directly or indirectly, as the standard with which other metals were compared.

The results indicate that, in general, the differences in conductivity of irons and steels are much smaller at high temperatures than at room temperatures. High-alloy steels have lower thermal conductivities than low-alloy steels. The thermal conductivities of irons and low-alloy steels decrease with increase in temperature. The conductivities of the high-alloy steels increase with increase in temperature; in other words, an increase in the amount of alloying constituents in iron causes, in general, a decrease in thermal conductivity and an increase in the temperature coefficient. The many and sometimes conflicting factors concerned make it practically impossible to generalize on the quantitative relationship of thermal conductivity and total alloy content of ferrous metals.

A fairly complete bibliography of data on the thermal conductivity of iron and steel is given.

CONTENTS

I. INTRODUCTION

Previous determinations of the thermal conductivities of iron alloys are surprisingly few. Hall[1] gives an excellent summary of the investigations made by Forbes, Lorenz, Angstrom, Neumann and others during the nineteenth century. A fairly complete bibliography of subsequent data relating to the thermal conductivity of iron and its alloys is appended to this paper.

The primary object of most of the earlier researches was to correlate thermal and electrical conductivities. The test material was of secondary importance. Later tests were made on present day structural materials and the results are more reliable and have more practical application. Information on the thermal conductivity of

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[1] E. H. Hall, concerning thermal conductivity of iron, Physical Review, vol. 10, p. 277, 1900.

structural materials over a range of temperature is of considerable importance within a limited field [2] in the selection of materials and in the design of structures.

In this paper are given results of the determination of the thermal conductivities of 20 miscellaneous irons and steels which were selected as typical examples of commercial materials used for a variety of purposes and were expected to have considerably different thermal conductivities. The data on the chromium-iron and chromium-nickel-iron alloys are of particular interest because of the lack of previous data on the thermal conductivity of stainless steels.

II. TEST METHOD

The method and apparatus used in the determinations given in this paper are described in detail in a separate paper.[3]

The apparatus was designed for comparative measurements and thus eliminated calorimetric or power-input determinations which are difficult to perform with uniformly high accuracy over a broad range of temperature. High-purity lead was used, either directly or indirectly, as the "standard" with which other metals were compared. The thermal conductivity of lead at ordinary temperatures is believed to be known with as high an accuracy as that of any metal.

The method consisted essentially in measuring the axial temperature gradients in two cylindrical bars, soldered together end to end. One end of the system was heated, and the other was cooled. The convex surface of the bars was protected from loss or gain of heat by a shield tube. After a steady state of heat flow has been attained, the heat flux is the same in both bars, and the conductivity at any point in either bar is inversely proportional to the temperature gradient at that point. If the absolute value of the conductivity of the metal of one bar is known at some temperature within the experimental range, the conductivity of the other metal can be calculated at all points where the temperature gradient has been measured.

III. MATERIALS AND RESULTS

The materials on which determinations were made are described in table 1.

The results of thermal conductivity determinations of the irons and low-alloy steels are shown graphically in figure 1. The results on the high-alloy steels, including chromium steels and a high-manganese nickel steel, are shown in figure 2, and those on the "eighteen-eight" type chromium-nickel steels in figure 3. Thermal conductivity values for different temperatures, interpolated from the experimental results, are listed in table 2. The value for the thermal conductivity of lead, 0.352 watts cm^{-1} deg^{-1} at 0 C (International Critical Tables, vol. 5, page 218) was used as the basis for all determinations.

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[2] M. S. Van Dusen, note on applications of data on the thermal conductivity of metals. Symposium on Effect of Temperature on the Properties of Metals, A.S.M.E.-A.S.T.M., p. 725, 1931.

[3] M. S. Van Dusen and S. M. Shelton, B.S.Jour. Research, vol. 12 (RP 668), p. 439, 1934.

TABLE 1.—*Chemical composition and previous history of materials*

Designation	Material	Chemical composition—percent													History
		T.C.	G.C.	C.C.	C	Mn	P	S	Si	Ni	Cr	W	Al	Ti	
C_1	Basic open-hearth iron				0.02	0.03	0.042	0.005							Hot rolled to 1-inch bar. Tested "as rolled".
C_2	Wrought iron				.04	.046	.136	.025	0.265						Hot rolled to 1-inch bar. Grade A. A.S.T.M. specification A 84-21. Tested in the direction of forging "as rolled".
C_3	Cast iron	3.93	3.34	0.59		.63	.134	.077	1.40						Ingot mold material from cupola furnace. Specimen machined from a sand-cast bar 1.11-inch diam. and tested in the "as cast" condition.
C_4	Cast iron	4.16	3.50	.66		.79	.120	.040	1.35						Ingot mold material from blast furnace. Specimen machined from a sand-cast bar 1.11-inch diam. and tested in the "as cast" condition.
S_1	High-carbon steel				.83	.27	.017	.015	0.16						Specimen machined from hot-rolled rod 1-inch in diameter. Bar was heated to 800 C for 2 hr in an electric furnace and furnace cooled.
S_1Q	Same				.83	.27	.017	.015	.16						After the thermal conductivity determination, specimen S_1 was normalized by heating to 900 C for 10 minutes and air cooled. Reheated to 800 C for 10 minutes and quenched in water at room temperature. Reheated to 250 C, for 1 hr and furnace cooled.
S_2	Low-nickel steel				.35	.56	.015	.020	.02	1.37	0.46				Basic open-hearth steel, poured at 1480 C to an 18 by 21 inch ingot. Hot rolled to 4 by 4 inches, then to a rod 1-inch in diameter. Normalized at 900 C.
S_3	Low-manganese steel				.51	1.65	.016	.023	.24	0.10					Basic open-hearth steel, poured at 1480 C to a 22 by 25 inch ingot. Hot rolled to 4 by 4 inches, then to a rod, 1-inch in diameter. Normalized at 900 C.
S_4	Tungsten steel				.35	0.75	.35	.028	.22	.17	.61	1.04			Acid open-hearth steel, poured at 1490 C to an 18 by 21 inch ingot. Hot rolled to 4 by 4 inches, then to a rod 1 inch in diameter. Normalized at 900 C.

TABLE 1.—*Chemical composition and previous history of materials*—Continued

Designation	Material	Chemical composition—percent													History
		T.C.	G.C.	C.C.	C	Mn	P	S	Si	Ni	Cr	W	Al	Ti	
S_5	Low-chromium steel				0.10	0.45	0.013	0.017	0.18		5.15				Hot rolled to 1½-inch round bar. Annealed.
A_1	Chromium steel				.08	.35	.020	.017	.20	0.05	15.19			430	Basic electric-furnace steel poured at 1490 C to a 12 by 12 inch ingot. Cogged to 4 by 4 inches, then rolled to a 1-inch round bar. Annealed at 845 C.
A_2	Chromium steel				.07	.09	.015	.010	.09	.23	12.00			403	Basic electric-furnace steel poured at 1500 C to an 8 by 8 inch ingot. Cogged to 4 by 4 inches, then rolled to a 1-inch round bar. Annealed at 845 C.
A_3	Chromium steel				.14	.19	.020	.015	.12	.70	14.60			430	Basic electric furnace steel poured at 1500 C to an 8 by 8 inch ingot. Cogged to 4 by 4 inches, then rolled to a 1-inch round bar. Annealed at 845 C.
A_4	High-chromium steel				.10	.40	.013	.008	.45	.18	26.00			446	Hot rolled to 1½-inch round bar. Annealed.
A_5	Chromium-aluminum steel.				1.10	.30			.47	.35	17.12		1.55		500-lb induction furnace. Poured at 1490 C to 8 by 8 inch ingot. Rolled to 4 by 4 inches, then to a 1-inch round bar. Normalized at 900 C.
A_6	Manganese-nickel steel				0.70–.80	12.–13.				3.00					Machined specimen received. Previous history unknown. (Chemical composition nominal).
A_7	Chromium-nickel steel				.07	.27				9.10	18.6				1-inch round bar. Heated to 735 C, held for 8 hr and cooled in diatomaceous earth.
A_8	Chromium-nickel steel				.11	.19				9.21	18.5			302	1-inch round bar. Heated to 1120 C and quenched in cold water.
A_9	Chromium-nickel steel				.24	.37				8.96	19.6				1-inch round bar. Heated to 735 C, held for 8 hr and cooled in diatomaceous earth.
A_{10}	Chromium-nickel steel				.24	.28				7.99	19.6				1-inch round bar. Heated to 1120 C and quenched in water.
$A_{10}A$	Chromium-nickel steel				.24	.28				7.99	19.6				After the thermal conductivity determination, specimen A_{10} was heated for 8 hr at 735 C and furnace cooled.
A_{11}	Chromium-nickel-titanium steel.				.07	.59	.013	.003	.47	9.12	18.08			321 0.34	Hot rolled 1½-inch round bar. Annealed.

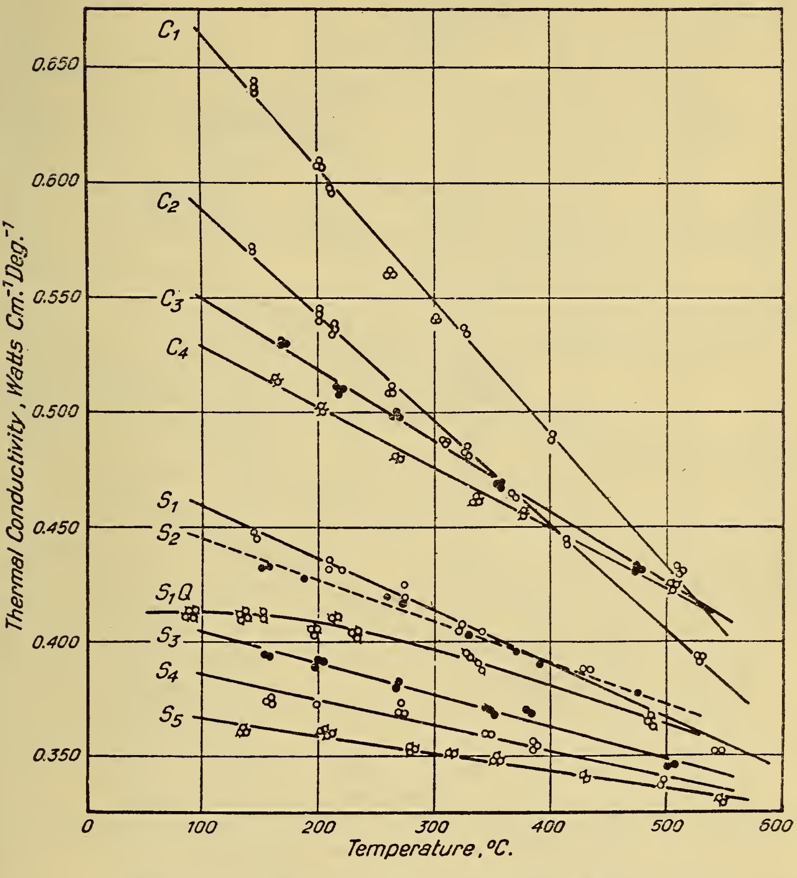

FIGURE 1.—*Thermal conductivity of irons and low alloy steels from 100 to 550 degrees Centigrade (212 to 1,020 degrees Fahrenheit).*

C_1—open hearth iron; approximately 99.9 percent iron.
C_2—wrought iron; approximately 99.5 percent iron.
C_3 and C_4—cast irons; approximately 4.0 percent carbon and 1.5 percent silicon.
S_1 and S_1Q—carbon steel; 0.83 percent carbon.
S_2—nickel steel; 0.35 percent carbon; 1.37 percent nickel; 0.46 percent chromium.
S_3—manganese steel; 0.51 percent carbon; 1.65 percent manganese.
S_4—tungsten steel; 0.35 percent carbon; 1.04 percent tungsten.
S_5—chromium steel; 0.10 percent carbon; 5.15 percent chromium.

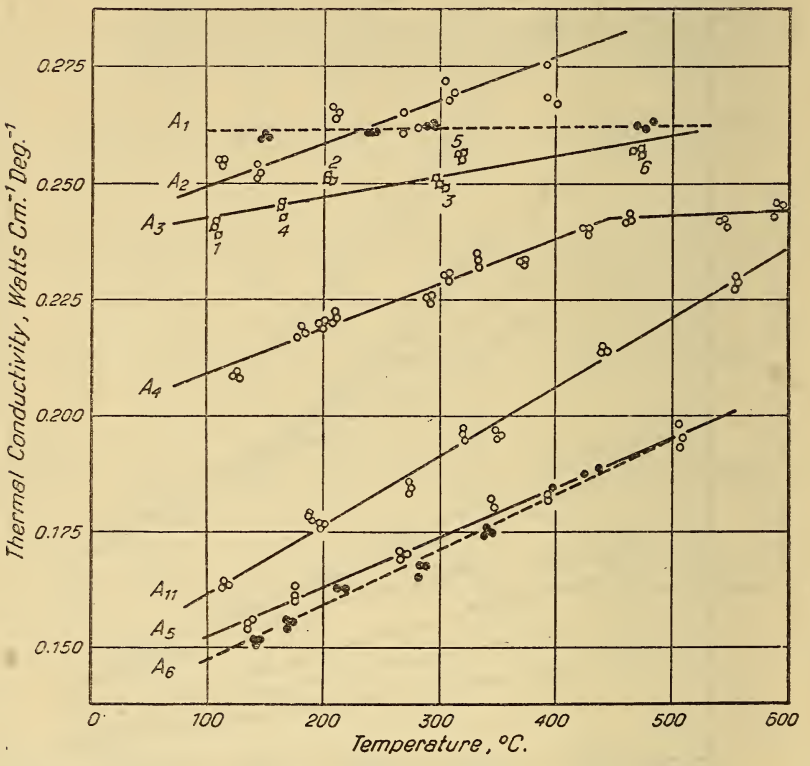

FIGURE 2.—*Thermal conductivity of high alloy steels from 100 to 600 degrees Centigrade (212 to 1,110 degrees Fahrenheit).*

A_1—chromium steel; 0.08 percent carbon; 15.19 percent chromium.
A_2—chromium steel; 0.07 percent carbon; 12.0 percent chromium.
A_3—chromium steel; 0.14 percent carbon; 14.60 percent chromium.
A_4—chromium steel; 0.10 percent carbon; 26.00 percent chromium.
A_5—chromium-aluminum steel; 1.10 percent carbon; 1.55 percent aluminum; 17.12 percent chromium.
A_6—manganese-nickel steel; 0.7 to 0.8 percent carbon; 12 to 13 percent manganese; 3.0 percent nickel.
A_{11}—titanium bearing "18-8" stainless; 0.07 percent carbon; 0.34 percent titanium.

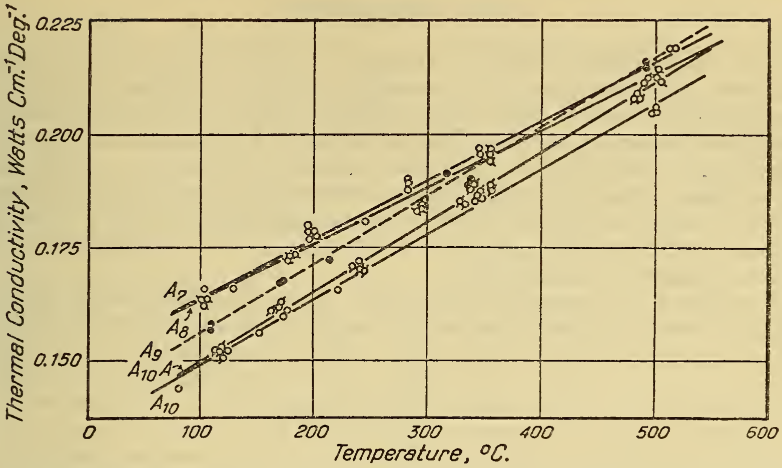

FIGURE 3.—*Thermal conductivity of "18–8" stainless steels from 100 to 550 degrees Centigrade (212 to 1,020 degrees Fahrenheit).*

A_7—0.07 percent carbon; 9.10 percent nickel; 18.6 percent chromium.
A_8—0.11 percent carbon; 9.21 percent nickel; 18.5 percent chromium.
A_9—0.24 percent carbon; 8.96 percent nickel; 19.6 percent chromium.
A_{10} and $A_{10}A$—0.24 percent carbon; 7.99 percent nickel; 19.6 percent chromium.

TABLE 2.—*Thermal conductivity, watts cm^{-1} deg^{-1}, interpolated for the temperatures listed from the experimental results*

Designation	Material	100 C	200 C	300 C	400 C	500 C
C_1	Basic open-hearth iron	0.665	0.607	0.549	0.491	0.435
C_2	Wrought iron	.589	.543	.497	.451	.405
C_3	Cast iron	.550	.519	.488	.458	.426
C_4	Cast iron	.528	.502	.476	.449	.422
S_1	Plain carbon steel	.458	.435	.413	.390	.367
S_1Q	Same, quenched	.412	.408	.396	.381	.364
S_2	Low-nickel steel	.445	.427	.409	.391	.372
S_3	Low-manganese steel	.403	.389	.376	.363	.349
S_4	Tungsten steel	.385	.371	.363	.352	.341
S_5	Low-chromium steel	.366	.358	.351	.343	.336
A_1	Chromium steel	.261	.262	.262	.262	.263
A_2	Chromium steel	.249	.259	.268	.277	--------
A_3	Chromium steel	.243	.247	.252	.256	.261
A_4	High-chromium steel	.209	.219	.229	.238	.243
A_5	Chromium-aluminum steel	.177	.188	.199	.210	.221
A_6	Manganese-nickel steel	.148	.160	.171	.183	.195
A_7	Chromium-nickel steel	.164	.177	.190	.203	.216
A_8	Chromium-nickel steel	.163	.176	.189	.201	.214
A_9	Chromium-nickel steel	.156	.172	.187	.202	.217
A_{10}	Chromium-nickel steel	.149	.164	.178	.193	.207
$A_{10}A$	Same, annealed	.150	.166	.181	.196	.212
A_{11}	Chromium-nickel-titanium steel	.161	.176	.191	.206	.221

The values relative to lead are believed to be accurate within 2 percent. Experimental data in the literature indicate that the thermal conductivity of lead at 0 C is known to an accuracy of 3 percent or better. If at any time the thermal conductivity of the lead standard is measured by an absolute method and the present accepted value is found to be in error, the data on all of the materials tested may be corrected by proportionate adjustment.

IV. DISCUSSION

The results indicate that, in general, the differences in conductivity of irons and steels are much smaller at high temperatures than at room temperatures. High-alloy steels have lower thermal conductivities than low-alloy steels. The thermal conductivities of iron and low-alloy steels decrease with increase in temperature. The conductivities of the high-alloy steels increase with increase in temperature; in other words, an increase in the amount of alloying constituents in iron causes, in general, an increase in the temperature coefficient of thermal conductivity.

The effect on thermal conductivity of small differences in composition is more marked in iron alloys having a small amount of alloying elements than in alloys with higher alloy concentrations. An additional and somewhat complicating factor is the nature of the alloy. For example, the total alloy content of cast iron (C_3) is greater than the alloy content of a plain carbon steel (S_1) but the thermal conductivity at 100 C of the cast iron was found to be approximately 20 percent higher than the conductivity of the plain carbon steel at the same temperature. The results on the plain carbon steel (S_1 and S_1Q) show that a heat treatment which resulted in a change in structural constitution produced an appreciable change in conductivity at lower temperatures. The many, and sometimes conflicting, factors concerned make it practically impossible to generalize on the quantitative relationship of thermal conductivity and total alloy content of ferrous metals.

With the exception of quenched plain carbon steel (S_1Q), the thermal conductivities of all the materials tested were found to be linear functions of temperature within the range of temperature in which measurements were made. An unusual "scatter" is noticeable in the plotted points representing the determinations on the chromium steel (A_2). The differences are irregular in character and the most probable explanation is that a structural change in the specimen took place with repeated heating in the apparatus. The irregular character of the "scatter" supports the belief that it cannot be attributed to experimental error. A typical example of "scatter" evidently due to experimental error or to a lack of homogeneity of the specimen is shown by the points representing the determination on steel A_3. The results of the first series of determinations at relatively low temperatures are represented by the groups of points numbered 1, 2, and 3 (fig. 2). The results of the second series at relatively high temperatures are represented by the groups 4, 5, and 6. The character of the "scatter" is the same for both series although the temperatures were quite different. A more complete investigation over a wider range of temperature is desirable but was not possible in the present apparatus.

The "18–8" chromium-nickel steels studied represent low-carbon steels (0.07 to 0.11 percent) in the annealed condition (A_7) and in the quenched condition (A_8) and high-carbon steels (0.24 percent) in the corresponding conditions annealed (A_9) and quenched (A_{10}). As shown by the curves in figure 3, the results on the two low-carbon steels coincided within the experimental error at low temperatures, and very nearly so at higher temperatures. The higher carbon specimens showed differences in both thermal conductivity and temperature coefficient over the whole temperature range. A greater difference in composition existed between the two high-carbon steels. In order to determine whether the differences in thermal conductivity of the high-carbon steels could be attributed to composition or to previous heat treatment, the quenched specimen was annealed and the thermal conductivity was redetermined. According to the results, the thermal conductivity of the reannealed steel was unchanged at low temperature, but at higher temperatures the annealed material had a higher conductivity than the quenched material. It is noteworthy, and possibly of some significance, that the thermal conductivity of the annealed steel was practically the same as that in the quenched state, but the temperature coefficient of the reannealed specimen $A_{10}A$ was of the same order of magnitude as that of the annealed specimen (A_9) of a different composition.

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