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THE THERMAL CONDUCTIVITY OF NICKEL

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Abstract—Thermal conductivity determinations have been made on five samples of nickel, two from 323°K to 1100° and 1300°K, two to 800°K and one to 600°K. The results are presented, together with those of electrical resistivity and these are discussed. Nickel resembles the other ferromagnetic metals, iron and cobalt in having a negative temperature coefficient of thermal conductivity when in the magnetic phase. The thermal conductivity of nickel reaches a minimum at the Curie temperature and has a positive temperature coefficient for the non-magnetic phase throughout the range of temperature studied. For this phase, the lattice component is found to be appreciable, to be relative temperature independent but to vary from sample to sample. In consequence, further work on nickel of varying purity and density is needed before it will be possible for the thermal conductivity of a particular sample to be predicted to within a few per cent from a knowledge of its electrical resistivity.

For nickel, iron and cobalt in the magnetic phase the reduced thermal conductivity, λ_T/λ_θ, is shown to be a function of reduced temperature, T/θ, but one which differs from that applicable to most other metals.

NOMENCLATURE

- T, absolute temperature [°K];
- θ, Debye temperature;
- λ, total thermal conductivity [W cm^{-1} deg^{-1}];
- λ_e, electronic component of thermal conductivity;
- λ_g, lattice component of thermal conductivity;
- ρ, total electrical resistivity [Ω cm];
- ρ_0, residual resistivity;
- ρ_I, component of resistivity due to crystal imperfections;
- ρ_T, component of resistivity due to thermal scattering;
- ρ_S, component of resistivity due to *s–d* scattering;
- L, Lorenz function ($\lambda\rho/T$) [V^2 deg^{-2}].

INTRODUCTION

SINCE the metal nickel has relatively good heat resistant properties it is not surprising that information on the thermal conductivity should be required in connection with various high temperature applications in which nickel might be used.

Figure 1 includes the values likely to be found if recourse is made to the usual reference books. At least two common sources, *Handbook of Chemistry and Physics*, 44th edition (1962–3) and the *Smithsonian Physical Tables* (1956) give only the very low values due to Angell [1], which even in 1917 were regarded as "contradictory to the facts already accepted" [2]. *Metals Reference Book* 3rd edition (1962) and *Metals Handbook* (1961) give values from 293° to 773°K which appear to be based on measurements made at the National Bureau of Standards for vacuum melted nickel of 99·94% purity [3]. These values are in general agreement with those of the Kaye and Laby *Tables of Physical and Chemical Constants* 12th edition (1959) and the *American Institute of Physics Handbook* 2nd edition (1963) which both extend the range to 973°K. In order to locate values at higher temperatures one needs to turn to more specialized treatments. A compilation by Goldsmith *et al.* [4] of the Armour Research Foundation, includes values to just over 1600°K obtained at that establishment by Fieldhouse *et al.* [5] for a sample of density 8·86 g cm^{-3}. Another useful compilation of available values is Volume 1 of the *Data Book* of the Thermophysical Properties Research Center according to which three further sets of measurements extend to temperatures of the order of 1000°K. These values, which are due to Honda

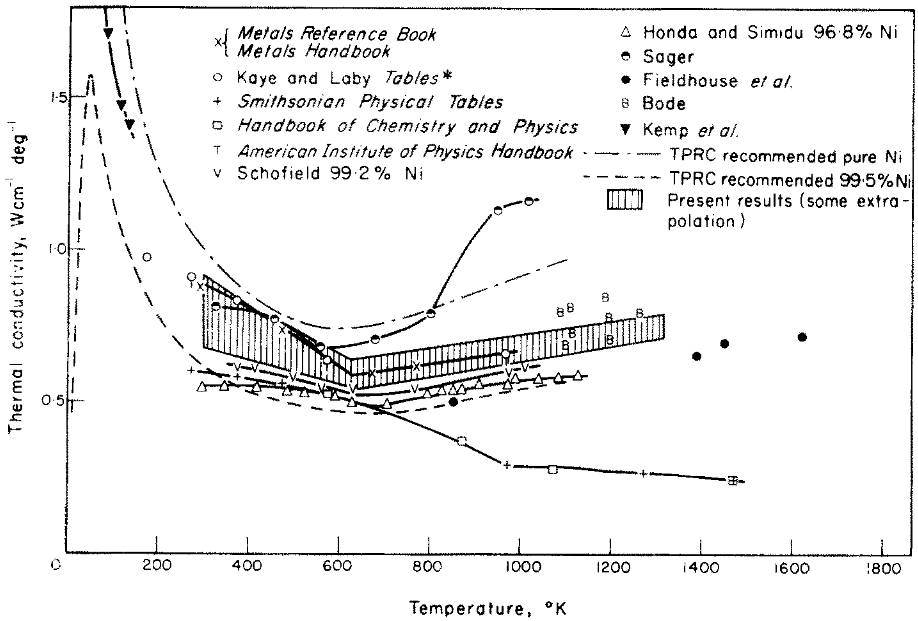

FIG. 1. Temperature variation of thermal conductivity of nickel: relation of new data (hatched area) to available information.

* Full title: *Table of Physical and Chemical Constants.*

and Simidu [2] for nickel of only 96·8% purity, Sager [6] and Bode [7] are included in Fig. 1. The earlier determinations made at the National Physical Laboratory by Schofield [8] for a sample of 99·2% purity are also shown. The results of Honda and Simidu and of Schofield are similar, with the values for the sample of lower purity on a curve that is lower by about 0·03 W cm^{-1} deg^{-1}.

Also included in the figure are the TPRC recommended curves for pure nickel and for nickel of 99·5% purity. At low temperatures these have been based on a general equation fitted with appropriate constants derived from just the two sets of available data [9, 10] whilst in the moderate and high temperature regions the curves are based directly on existing data. Owing to the shortage of reliable values for nickel at both low and high temperatures it seems likely that some revision of these recommendations may become necessary. Schofield's measurements are known to one of the writers to have been undertaken with much care, and it is considered that the curve for 99·5% Ni should be located above the line drawn through his points.

Figure 1 clearly shows the need for more experimental determinations and emphasizes both the need for revision of some of the reference-book values and the critical assessment that is often desirable before such values are employed for vital calculations.

The National Physical Laboratory has made measurements on several samples of nickel and the values for λ have, with a certain amount of extrapolation, been found to lie within the hatched portion of Fig. 1. These results are presented and discussed in the following sections.

DETAILS OF SAMPLES AND EXPERIMENTAL METHOD

The five samples† for which results are to be presented and discussed are the following:

1. A tubular sample of electrolytic nickel of 1·272 cm internal diameter, 1·908 cm external diameter from which a test specimen some 20 cm in length was cut. This was supplied by the Castner Kellner Alkali Co. Ltd. The density was measured as 8·61 g cm^{-3} and a spectroscopic

† The numbers 1–5 serve to identify the samples.

analysis made subsequently by the International Nickel Co. (Mond) Ltd., indicated that Cr, Co, Mo, Ti, Al, Si, Mn, Zr, Mg, Cu, Sn and Zn were each present in amounts below 0·01%, Pb under 0·005%, B under 0.002%, Fe under 0·03% whilst Bi was not detected.

2. A tubular sample of electrolytic nickel of 0·634 cm internal diameter, 2·801 cm external diameter and about 19 cm length was supplied by the National Engineering Laboratory. Its density was measured as 8·90 g cm^{-3}. No analysis has been made, although it was stated to be of very high purity.

3. The nickel was supplied by the Atomic Energy Research Establishment in the form of three tubes of 1·589 cm external diameter, 1·538 cm internal diameter and about 43 cm length. From these tubes 32 strips each approximately 0·95 cm wide and 14 cm long were cut and pressed together to form a compact specimen. The density as determined by weighing in air and water was 8·9 g cm^{-3} and the cross-sectional area of the composite sample was drived from observations of its weight and length.

The nickel content was stated to be 99·5 $\pm$ 0·1%, the main impurities being Co, 0·1 to 0·2%; Si, 0·1 to 0·2%; Fe, 0·04%; Mg, 0·03%; and Cr, 0·01%.

4. A rod of commercial nickel 2·54 cm in diameter and about 20 cm in length was supplied by the Explosives Research and Development Establishment for thermal conductivity measurement over the range 50° to 300°C. Neither the composition nor density was determined.

5. A nickel rod, 0·5 cm in diameter and 15 cm in length, was obtained from Messrs Johnson, Matthey Co. Ltd. (Laboratory No. 4497). It was stated to be of high spectrographic purity; lines due to Si, Ca, Al, Ag and Cu had been faintly visible and those of Mg, Na and Li very faintly visible. The density was measured and found to be 8·91 g cm^{-3}.

This specimen would seem to be from the same supply as that studied at low temperatures by Kemp *et al.* [9]. At 293°K and 4·2°K the measured values for ρ of 7·17 $\times$ 10^{-6} and 0·067 $\times$ 10^{-6} Ω cm can be compared with those of 7·22 $\times$ 10^{-6} and 0·0347 $\times$ 10^{-6} Ω cm reported by these workers. Their lower ρ_0 suggests that their specimen may have been of higher purity.

Each specimen has been screwed, or otherwise securely fixed, to a rod of Armco iron of similar dimensions and known properties and λ determined by means of longitudinal heat flow methods previously described [11]. In the course of these experiments, a few measurements of ρ were made, whilst for specimens 1, 4 and 5 independent measurements of ρ were carried out with these samples uniformly heated within a tubular electric furnace.

RESULTS

Experimental values of λ and ρ obtained for the five nickel samples are shown in Figs. 2 and 3 respectively. In Fig. 3 smooth curves have been drawn through the experimental points for samples 3, 4 and 5. The points for sample 1 lie so close to those of sample 5 that no separate curve has been drawn. For sample 2, few points were obtained as these measurements were made only occasionally in the course of the thermal conductivity experiment.

Values read from the smooth curves are given in Tables 1 and 2. These tables also include derived values for L whilst its temperature variation for each sample is shown in Fig. 4.

DISCUSSION OF THE RESULTS

(*a*) *Thermal conductivity*

For each sample, from room temperature to about the Curie temperature λ is seen to fall sharply and steadily with increase in temperature. In this respect nickel resembles the other ferromagnetic metals, iron and probably cobalt [12]. Above the Curie temperature the four samples studied to higher temperatures have positive temperature coefficients, whereas values of λ for iron have recently been found [13, 14] to become relatively constant above its Curie temperature (1043°K) and to assume a positive temperature coefficient above the alpha to gamma phase transition temperature (1184°K). It would seem that iron and nickel differ from most other pure metals, certainly from others of comparable conductivity, in that the sign of the temperature coefficient at high temperatures is positive. At room temperature the values of λ for the purest samples of iron, nickel and cobalt are about 0·8, 0·9 and 0·85 W cm^{-1} deg^{-1} respectively but at 1300°K owing to the much lower Curie

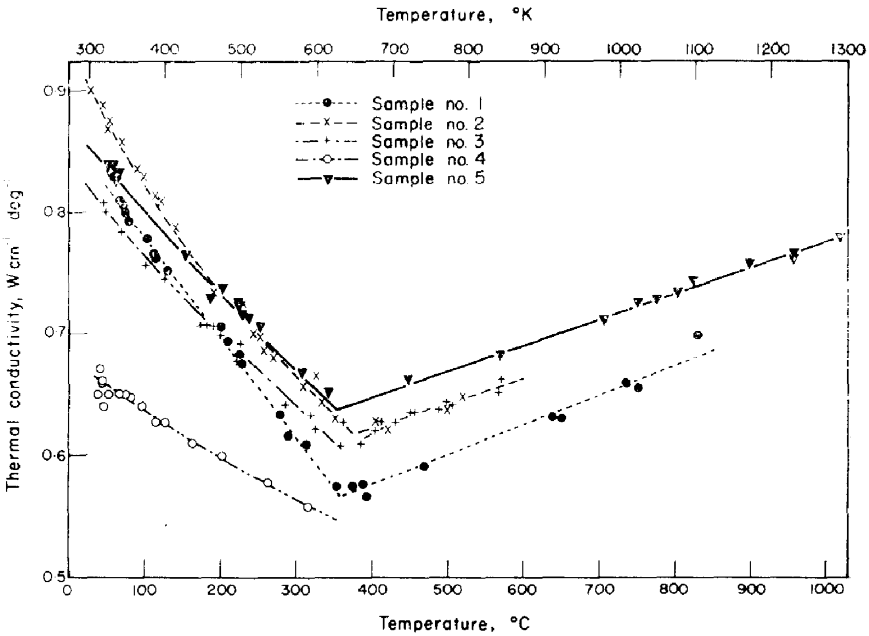

FIG. 2. Thermal conductivity of five nickel samples.

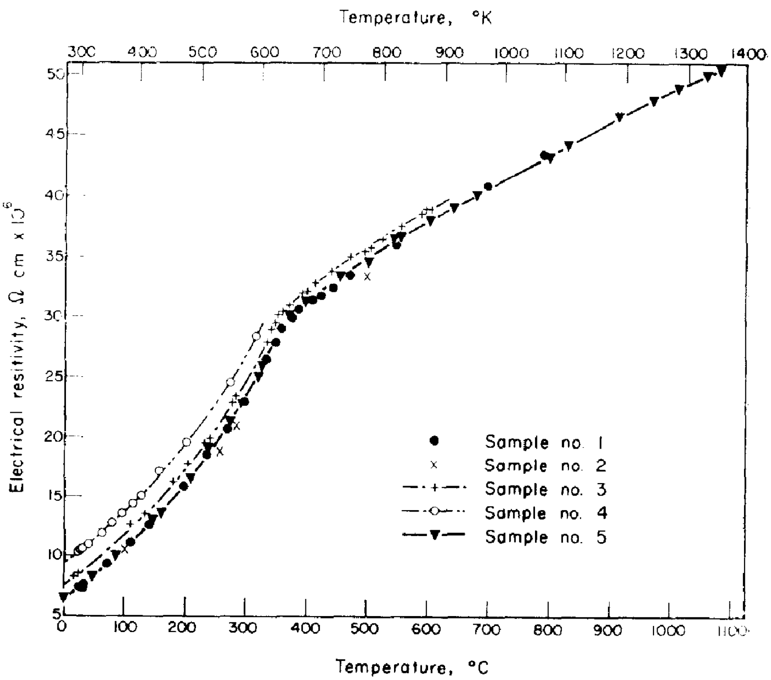

FIG. 3. Electrical resistivity of five nickel samples.

Table 1. Values of λ, ρ, and L for nickel samples 1 to 4

T	Sample 1			Sample 2	Sample 3			Sample 4		
	λ	$10^6\ \rho$	$10^8\ L$	λ	λ	$10^6\ \rho$	$10^8\ L$	λ	$10^6\ \rho$	$10^8\ L$
293	—	7·1	—	—	—	8·3	—	—	10·1	—
323	0·822	8·3	2·11	0·875	0·800	9·6	2·38	0·657	11·3	2·30
423	0·738	13·0	2·27	0·777	0·731	14·3	2·47	0·616	16·3	2·37
523	0·655	19·4	2·43	0·697	0·669	20·6	2·63	0·581	22·8	2·53
623	0·573	28·0	2·57	0·633	0·611	29·7	2·91	0·547	31·5	2·77
723	0·588	32·8	2·67	0·632	0·632	34·1	2·98	—	—	—
823	0·612	36·1	2·68	0·652	0·652	37·3	2·96	—	—	—
923	0·637	39·3	2·71	—	—	—	—	—	—	—
1023	0·662	42·4	2·74	—	—	—	—	—	—	—
1123	0·687	45·2	2·77	—	—	—	—	—	—	—

Table 2. Values of λ, ρ, L, ρ_{calc}, λ_{eL}, λ_{gL}, λ_{eB} and λ_{gB} for sample 5

T	λ	10^6	$10^8\ L$	$10^6\ \rho_{calc}$	λ_{eL}	λ_{gL}	λ_{eB}	λ_{gB}
293	—	7·1	—	7·04	—	—	—	—
323	0·837	8·3	2·15	8·2$_5$	0·954	−0·117	0·832	0·005
423	0·766	13·1	2·37	13·1	0·791	−0·025	0·724	0·042
523	0·701	19·4	2·60	19·5$_5$	0·661	0·040	0·622	0·079
623	0·640	28·3	2·91	27·6	0·540	0·100	0·517	0·123
723	0·658	33·2	3·02	—	0·533	0·125	0·514	0·144
823	0·679	36·4	3·00	—	0·554	0·125	0·536	0·143
923	0·701	39·2	2·98	—	0·576	0·125	0·560	0·141
1023	0·723	42·1	2·98	—	0·595	0·128	0·578	0·145
1123	0·745	44·7	2·97	—	0·615	0·130	0·599	0·146
1223	0·766	47·5	2·98	—	0·631	0·135	0·615	0·151
1323	0·786	49·8	2·96	—	0·650	0·136	0·635	0·151

temperature of nickel, the value for high purity nickel is about twice that of pure iron. Measurements on cobalt, have not yet been determined above 430°K, but the discussion that follows will indicate that it is not likely to exceed that of nickel. At 1300°K, λ for nickel is probably exceeded only by that of silver and copper, although these are nearing their melting points, tungsten, molybdenum and possibly by gold, iridium, rhodium, ruthenium and beryllium, whose properties have yet to be measured at such high temperatures.

Another difference that is apparent when the results of Fig. 2 are considered with regard to the collected results for irons of differing purity is the much wider spread that is evident in the high temperature curves for nickel. Indeed, in the region of the Curie temperature irons and steels tend to converge much more towards a common value. Part of the difference could be due to the fact that in the case of nickel the samples include an electrolytic nickel of lower density as well as samples of varying purity. This matter will be discussed further when the other properties ρ and L are considered.

Before passing on to these other properties it is considered desirable and of interest to refer to Fig. 5, which directs attention to another manner in which the behaviour of λ of these three ferromagnetic metals differs from that of most other metals.

This figure is based on the work of Cezairliyan [15] who showed that whereas for most metals at moderate and high temperatures λ can

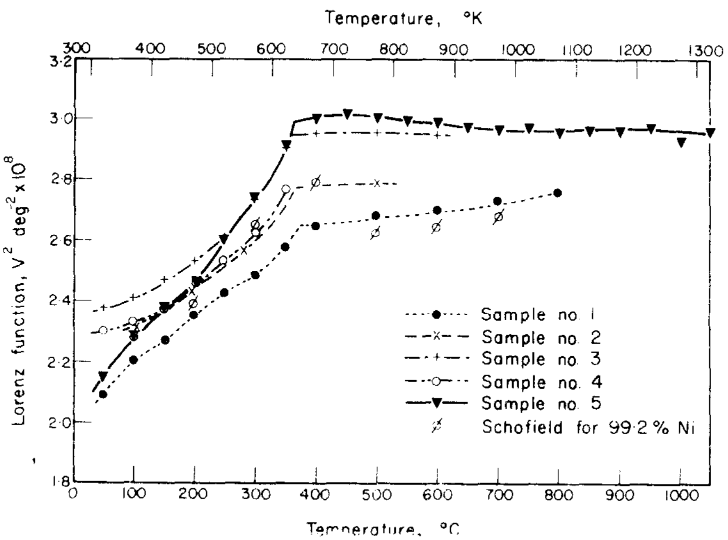

FIG. 4. Lorenz function of five nickel samples.

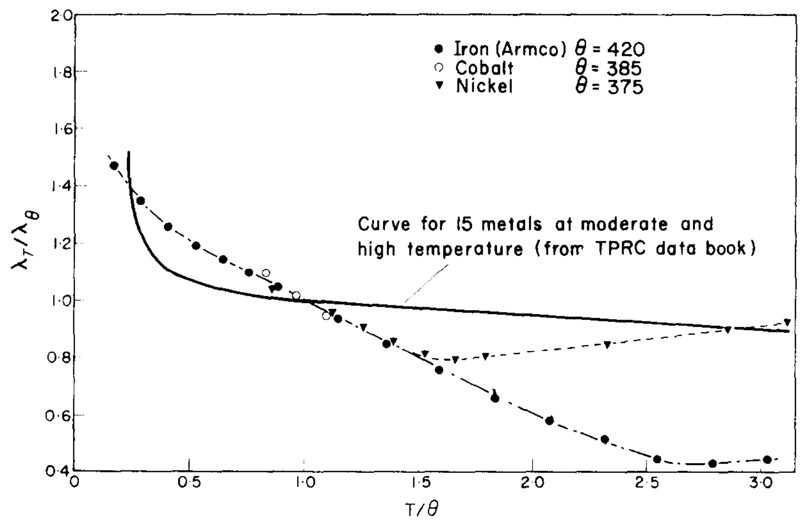

FIG. 5. Reduced thermal conductivity as a function of reduced temperature.

be correlated to lie within a few per cent of a single curve by plotting λ_T/λ_θ against T/θ, the values for a few metals including nickel lie on a quite different curve.

The curve which Cezairliyan obtained for fifteen metals is reproduced in the *Data Book* of the Thermophysical Properties Research Center at which the work was undertaken and is labelled accordingly in Fig. 5. It is fitted by metals for which λ decreases with increase in temperature. In his report, however, Cezairliyan found that the results for beryllium, bismuth, iron and nickel did not obey this general correlation but fitted a different curve. He stated that the reason for the failure of a single universal curve to correlate all metals may be that θ is not the true critical parameter to be used to obtain the critical λ. It is perhaps more probable that a third critical parameter may be necessary and this is a problem which requires further exploration.

In Fig. 5 the present results for sample 5, together with those for Armco iron [16] and cobalt [12] are treated in a similar manner. No values for cobalt at temperatures above normal were available to Cezairliyan. Below the Curie temperature the points for these three ferromagnetic metals conform, as Cezairliyan found, to a single but distinctly different curve from that for fifteen other metals. Above their Curie temperatures the points for iron and nickel deviate from this curve and differ considerably. These results support the suggestion made that further parameters must be introduced before all data for λ can be reduced to a single curve, and leaves future investigators to determine how best this can be achieved. The correlation is, however, of interest, and emphasizes the need for the measurements on cobalt to be extended to temperatures above its Curie point.

(b) Electrical resistivity

Unfortunately these results are not complete, but confining attention to specimens 1, 3 and 5, it is clear that whereas values of λ cover a slightly increasing range of the order of 10 per cent at temperatures from 323° to 923°K, the corresponding values of ρ converge from a range of about 11 to 3 per cent. This indicates that the different samples must have differences in λ_g, that exceed the differences in λ_e.

The general shape of these curves closely resembles the resistivity temperature curve of iron, and it is of interest to consider how the equation

$$\rho = a + bT + cT^3 \qquad \text{(i)}$$

applies to the results for sample 5.

This equation had been found to hold for iron by Bäcklund [17], who had promised that in a later paper it would also be applied to the resistance data of nickel. Bäcklund had suggested that the three terms of this equation can be compared with those of the equation

$$\rho = \rho_I + \rho_T + \rho_S \qquad \text{(ii)}$$

for a transition metal. Here the first component is temperature independent while the last is represented by the T^3 term, and should become independent of temperature for magnetic metals above the Curie temperature. For gamma iron the resistivity–temperature curve had a slope that agreed closely with that given by the thermal scattering term.

For sample 5, ρ was measured at 77°K, liquid nitrogen temperature, and found to be

$$0{\cdot}584 \times 10^{-6}\ \Omega\ \text{cm}.$$

Using this value, and values at 273°K and 469°K of $6{\cdot}27 \times 10^{-6}$ and $15{\cdot}8 \times 10^{-6}\ \Omega$ cm respectively, the equation

$$\rho = -1{\cdot}21 + 2{\cdot}29 \times 10^{-2}\,T + 6{\cdot}1 \times 10^{-8}\,T^3 \qquad \text{(iii)}$$

has been derived.

The column headed ρ_{calc} in Table 2 contains values calculated from this equation and these values fit reasonably well with the experimentally determined data for temperatures below the Curie point. Above the Curie temperature the mean slope of the resistivity temperature curve is, however, about $2{\cdot}7 \times 10^{-2}$, or almost 20 per cent greater than that given by the second term of equation (iii). At 1300°K, ρ of nickel is about $50 \times 10^{-6}\ \Omega$ cm, whereas that of iron is greater by a factor of about 2·3.

(c) Lorenz function and the derived electronic and lattice components of thermal conductivity

Values of L are seen from Fig. 4 to be far from constant and to show differences from sample to sample which tend to persist throughout the range of temperature studied. The values due to Schofield for a 99·2% nickel have been included in the figure and, except where the Curie temperature may have caused uncertainties, they are seen to agree to within some 3 per cent with those for sample 1 of the present investigation.

For each sample L is less than the theoretical value of $2{\cdot}45 \times 10^{-8}\ \text{V}^2\ \text{deg}^{-2}$ at normal temperatures, but increases rapidly to exceed the theoretical value at the Curie temperature, and, above this, to be relatively independent of temperature. In this region, it is greatest for sample 5, a sample of high density and purity and least for sample 1, one of much lower density and purity. By making the usual assumption that

$$\lambda_g = \lambda - \lambda_e \qquad \text{(iv)}$$

where

$$\lambda_e = \frac{2{\cdot}45 \times 10^{-8}\,T}{\rho} \qquad \text{(v)}$$

it is found that at 800°K, λ_g has a value of 0·125 W cm^{-1} deg^{-1} for sample 5, but one of only 0·055 W cm^{-1} deg^{-1} for sample 1.

Values obtained in this way for both components for sample 5 have been included in Table 2 in the columns headed λ_{eL} and λ_{gL} respectively.

Above the magnetic transformation point both components are seen to increase with increase in temperature, but λ_e is increasing at a much faster rate. It is more usual for λ_e to be relatively constant and for λ_g to decrease with increase in temperature, indeed to vary as T^{-1}. It would seem that abnormal complications are present with nickel. These may help to explain the low values of L evident at lower temperatures which even at θ (375°K) remain below

$$2{\cdot}45 \times 10^{-8}\ \mathrm{V^2\ deg^{-2}}$$

and would, therefore, lead to quite unacceptable negative values for λ_{gL}.

Bäcklund has suggested that some of this difficulty can be overcome by evaluating λ_e by means of the relation

$$\lambda_e = \frac{2{\cdot}45 \times 10^{-8}\, T}{\rho - a} \qquad \text{(vi)}$$

a being the temperature independent term of equation (i). In this way he obtained for iron, values of λ_g which decreased with increase in temperature from 100°K upwards and which were regarded as being more acceptable.

For sample 5, $a = -1{\cdot}21$

hence

$$\lambda_e = \frac{2{\cdot}45 \times 10^{-8}\, T}{\rho + 1{\cdot}21} \qquad \text{(vii)}$$

and values of λ_e derived by means of this equation have been included in Table 2 in the column headed λ_{eB}. The column headed λ_{gB} gives corresponding values of λ_g.

By comparing the two sets of values derived for λ_g it is apparent that this method enables positive values to be obtained to rather lower temperatures, but that both sets of values increase rapidly with temperature up to the Curie temperature then level off, and finally assume a small positive coefficient. In this high temperature region the values derived from the modified equation are greater by some 12 per cent. Since for nickel, λ_g remains large, it is clear that no modification of the type introduced by Bäcklund can result in a value of λ_g that has the anticipated inverse temperature relationship.

The large relatively constant values for λ_g recently reported for titanium carbide [18, 19] as well as for zirconium carbide [20, 21] have been considered to present a problem that still needs explaining. The present work shows that nickel when above the Curie temperature behaves similarly.

(d) *Prediction of thermal conductivity from electrical resistivity*

When measurements of both λ and ρ are available for several samples of the same metal, or for metals and alloys of the same group it is often possible to correlate the data to within a few per cent of a single curve by relating λ to T/ρ. The method was first suggested by Smith and Palmer [22] as a means of deriving values of λ for copper and its alloys and many subsequent applications of the method have recently been brought together [23]. For nickel and its alloys Fine [24] has suggested

$$\lambda = 2{\cdot}13 \times 10^{-8}\, T\rho^{-1} + 0{\cdot}84 \qquad \text{(viii)}$$

When the present results are examined in the light of this equation the predicted values are found to differ by from about +11 per cent to −18 per cent. Whilst these extremes lie within the ±20 per cent claimed by Fine, they are larger than those that were obtained when many other groups of metals were similarly treated.

The two phases, magnetic and non-magnetic, and the large and variable values of λ_g for the specimens studied must contribute towards these differences and help to make nickel a poor subject for correlations of this simple type. Indeed, until further work has been carried out leading to an improved correlation or a better understanding of the effects of variations in purity and density, nickel must be regarded as a metal for which experimental determinations are necessary whenever reasonably accurate values of λ are required for a particular sample of the metal.

ACKNOWLEDGEMENTS

The authors are indebted to the suppliers named above of specimens 1 to 4 for their help in allowing the results of measurements made on their behalf to be included in this paper, and to their colleagues, Margaret J. Woodman and A. E. Langton, who have assisted with the experimental work. The measurements made on sample 5 and the preparation of this account have formed part of the general research programme of the Basic Physics Division of the National Physical Laboratory. The paper is published with the approval of the Director of the Laboratory.

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Résumé—Des déterminations de la conductivité thermique ont été faites sur cinq échantillons de nickel, deux de 323°K à 1100° et 1300°K, deux à 800°K et une à 600°K. Les résultats sont présentés, en même temps que ceux de la résistivité électrique et sont discutés. Le nickel ressemble aux autres métaux ferromagnétiques, le fer et le cobalt, en ce qu'il a un coefficient négatif de variation en fonction de la température du coefficient de conductibilité thermique lorsqu'il est dans la phase magnétique. La conductivité thermique du nickel atteint un minimum au point de Curie et a un coefficient positif de variation en fonction de la température pour la phase non-magnétique dans la gamme de températures étudiée. Pour cette phase, on trouve que la composante de réseau est appréciable, qu'elle est relativement indépendante de la température mais qu'elle varie selon l'échantillon. En conséquence, on a besoin de continuer à travailler sur du nickel de pureté et de densité variable avant qu'il soit possible de prédire la conductivité thermique d'un échantillon particulier à quelques pour cent près à partir de la connaissance de sa résistivité électrique.

Pour le nickel, le fer et le cobalt dans la phase magnétique on montre que la conductivité thermique réduite, λ_T/λ_θ, est une fonction de la température réduite, T/θ, mais qui diffère de celle applicable à beaucoup d'autres métaux.

Zusammenfassung—Von fünf Nickelproben, zwei von 323°K bis 1100°K und 1300°K, zwei bis 800°K und eine bis 600°K, wurde die Wärmeleitfähigkeit bestimmt. Die Ergebnisse werden diskutiert und zusammen mit dem elektrischen Widerstand angeführt. Nickel gleicht den anderen ferromagnetischen Metallen Eisen und Kobalt, da die Wärmeleitfähigkeit in magnetisiertem Zustand einen negativen Temperaturkoeffizienten aufweist. Die Wärmeleitfähigkeit von Nickel erreicht ein Minimum bei Curie-Temperatur und hat im nicht magnetisiertem Zustand einen positiven Temperaturkoeffizienten im ganzen untersuchten Temperaturbereich. Für diesen Zustand findet man, dass die Gitterkomponente abschätzbar, relativ temperaturunabhängig, aber von Probe zu Probe verschieden ist. Als Folge davon werden weitere Arbeiten an Nickel verschiedener Reinheit und Dichte nötig, ehe es möglich sein wird, die Wärmeleitfähigkeit einer besonderen Probe auf einige Prozent genau aus der ihrem bekannten elektrischen Widerstandes vorherzusagen.

Für Nickel, Eisen und Kobalt in magnetisiertem Zustand wird gezeigt, dass die reduzierte Wärmeleitfähigkeit λ_T/λ_θ eine Funktion der reduzierten Temperatur T/θ ist, aber eine Funktion, die sich von der auf die meisten anderen Metalle anwendbaren unterscheidet.

Аннотация—Теплопроводность никеля определялась на пяти образцах, два из которых находились при температуре от 323°K до 1100° и 1300°K, два до 800°K и один до 600°K. Приводятся и рассматриваются результаты измерений теплопроводности, а также удельной электропроводности. Никель напоминает другие ферромагнитные металлы, железо и кобальт, тем, что в магнитной фазе имеет отрицательные температурные коэффициенты теплопроводности. Теплопроводность никеля достигает минимума при температуре Кюри и имеет положительный температурный коэффициент для немагнитной фазы в диапазоне исследовавшихся температур. Найдено, что для этой фазы составляющая решетки довольно ошутима, относительно не зависит от температуры, но разная для образцов. Следовательно, прежде чем можно будет рассчитать теплопроводность отдельного образца с точностью до нескольких процентов, зная его удельную электропроводность, нужно провести дальнейшее исследование никеля различной чистоты и плотности.

Показано, что для никеля, железа и кобальта в магнитной фазе приведенная теплопроводность λ_T/λ_θ является функцией приведенной температуры T/θ, но она отличается от теплопроводности большинства других металлов.