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Thermal and Electrical Conductivities of Mo-Re Alloys in the Superconducting and Normal States

E. Lerner and J. G. Daunt*
Department of Physics, Ohio State University, Columbus, Ohio

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This paper gives details of research carried out on the low-temperature properties of Mo-Re alloys in the superconducting and normal states. Measurements were made on a variety of Mo-Re alloys in various states of anneal, the alloys being in the form of fine wires, as suitable for the winding of high-field superconducting solenoids. Micrograph studies were made to determine the percentage of the various phases present in each specimen. The low-temperature measurements covered observations on the various specimens of the electrical resistivity and the thermal conductivity as functions of temperature and magnetic field. The measurements yielded evaluations of two of the three critical magnetic fields, H_{c2} and H_{c3}, as functions of temperature and alloy constitution, the transition temperatures T_c, and the Landau-Ginzburg parameter κ. Detailed comparisons of the results are made with theoretical predictions and with results by previous authors on similar high-field superconducting alloys.

1. INTRODUCTION

SINCE high-field superconductors, such as are currently used in the construction of solenoidal magnets, are of topical interest, experimental studies were carried out on the properties of Mo-Re alloys. This alloy, which is classified as a "high-field" superconductor, was chosen since its superconductivity can be quenched in fields of less than about 40 kG, a field that is readily attainable in the laboratory, and since it was desired to study the properties of the normal state also. Moreover, some studies of the field direction dependence of the magnetic transition in Mo-Re wires had already been made by one of us previously.[1] One of the primary motivations of the work was the desire to make a wide variety of different measurements (resistivity, thermal conductivity, magnetic moment, etc.) on actually the *same* sample of each alloy in various states of anneal. It was anticipated that such a study would yield a pattern of behavior showing some inner consistency.

This paper covers the measurement of the electrical resistivity and the measurement of the thermal conductivity of various Mo-Re alloys in the form of fine wires and in various states of anneal. Each group of measurements is discussed in detail, comparisons being made with theory and, where possible, with previous experimental studies on similar high-field alloys. Evaluations are given of, for example, T_c, H_{c2}, H_{c3}, κ for the various alloys and some conclusions have been reached concerning the role played in the behavior of these alloys by annealing and by the presence of the σ phase.

Magnetic measurements on the same samples will be reported in a subsequent publication.

2. SPECIFICATION OF THE SAMPLES

In the experiments two different concentrations of the Mo-Re alloy were used, namely: 52–48% and 60–40% (weight %), at several states of anneal. All samples were from one spool of wire for each concentration, and they were supplied by Chase Brass & Copper Company. The chemical analyses are given in Table I. The 52–48% samples were 0.024 cm diam and the 60–40% 0.027 cm diam.

The phase diagram for the molybdenum-rhenium system is well known.[2] The 52–48% contains two phases, β and σ, below about 1250°C, whereas the 60–40% has only the β phase up to melting point. The β phase is a body-centered cubic structure and the σ phase is a complex tetragonal structure. The amount of the secondary σ phase at room temperature depends on the state of anneal of the sample. Table I lists all the samples used in the experiments with specification of their states of anneal and of the percentage of the σ phase present. Assessment of the fraction of σ phase was made from microphotography. Figure 1 shows some typical microphotographs of the samples studied. We are indebted to Dr. W. H. Jones and Dr. G. W. Cunningham of Battelle Memorial Institute for their help in sample annealing and analysis.

3. THE ELECTRICAL RESISTIVITY

(a) Experimental Arrangements

For measurements of the electrical resistance of the samples in the temperature range 1–4.2°K, the samples were immersed in a liquid-helium bath and surrounded by a superconducting solenoid capable of producing axial fields up to 50 kG, parallel to the sample length. The superconducting solenoid used was a NbZr solenoid supplied by Westinghouse Corp. with working volume of $\frac{1}{2}$ in. i.d. and $3\frac{3}{4}$ in. long. The temperature of the bath was found by measurement of the vapor pressure, using the 1958 He^4 scale of temperature.[3]

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* Present address: Stevens Institute of Technology, Hoboken, N. J.

[1] J. G. Daunt, M. Kreitman, W. Baltensperger, and J. L. Olsen, Cryogenics **2**, 212 (1962).

[2] J. M. Dickinson and L. S. Richardson, Trans. Am. Soc. Metals **51**, 1055 (1959).

[3] F. G. Brickwedde, H. van Dijk, M. Durieux, J. R. Clement, and J. K. Logan, Natl. Bur. Std. (U. S.), Monograph No. 10, 5 (1960).

TABLE I. States of anneal, percentage of σ phase and chemical analyses of Mo-Re samples.

Sample[b]	Annealing specifications	% σ phase	Chemical[a] analysis weight %
U-1	As received. 90% cold work.	Masked by cold work	Al- <0.0005 B- 0.0001 Ca- 0.0001 Co- 0.0003 Cr- 0.0003 Cu- 0.0002 Fe- 0.0070 Mg- 0.0001 Mn- 0.0004 Mo- 52.0000 Ni- 0.0004 Sn- 0.0002 Ti- 0.0002 Zr- 0.0002 Na- 0.0002 K- 0.0002 C- 0.0030 Si- 0.0006 H- 0.0005 N- 0.0010 O- 0.0040 Re- 47.9845
A-1	Annealed at 1250°C during 19 h. Cooled slowly.	19%	
A-2	Annealed at 1250°C during 19 h. Quenched in water.	22%	
A*-1	Same as A-1, after low-temperature thermal cycling.	44%	
A*-2	Same as A-2, after low-temperature thermal cycling.	28%	
A-3	Annealed at 2000°C during 1 h. Cooled slowly.	<1%	
A*-3	Same as A-3, after low-temperature thermal cycling.	<1%	
A-4; A-5	Annealed at 1100°C during 1 h. Cooled slowly.	Masked by cold work	
A-6; A-7	Annealed at 1100°C during 19 h. Cooled slowly.	50%	
U-2	As received. 90% cold work.	None	Same as above with Mo-(59.5–60.5%) Re-(39.5%)
B-1; B-2	Annealed at 1100°C during 1 h. Cooled slowly.	None	
B-3; B-4	Annealed at 1100°C during 19 h. Cooled slowly.	None	

[a] Quoted by Chase Brass & Copper Company.

[b] For an explanation of the asterisks against the letter symbols of the samples, see the end of Sec. 4(b).

The samples, which were 3 cm long, were ultrasonically "tinned" with indium in four different places to which current and potential leads were soldered also with indium. The resistances were measured using standard dc potentiometric techniques with a measuring current of 10 mA.

For measurements of the electrical resistivity as a function of temperature in the range 4–300°K another cryostat was used. The samples (two for each run) were placed in an enclosed vacuum-tight cylindrical copper can which was filled with helium exchange gas and which had a heater wound on its external surface. The sample temperature was measured by an Allen-Bradley carbon resistor (nominal room-temperature resistance 200 Ω, $\frac{1}{2}$ W) which was mounted inside the same copper can and located near the samples.

The heater wound around the copper can was made of 137 turns of a No. 30 Evanohm wire, and its total resistance at room temperature was 180 Ω. The copper can was suspended by nylon tube inside a vacuum jacket which was immersed in the liquid He^4 bath. The nylon tube connected to a $\frac{1}{8}$-in. Cu-Ni tube which led to the top of the cryostat and which served to evacuate and to introduce exchange gas into the copper sample chamber. It also served to carry the electrical leads from room temperature to the samples and to the carbon resistance thermometer, etc. All leads were thermally grounded to the copper parts of the sample chamber in order to avoid direct heat conduction to sample and carbon resistor. The nylon-metal joints were made by slipping the nylon tube over shaped brass bushings. This arrangement proved to be very efficient; no leaks were observed, which was attributed to the fact that nylon contracts much more than brass.

The temperature of the sample can for the experiments above 4.2°K was increased or decreased by means of the heater. It was possible with this arrangement to raise the temperature to room temperature.

The resistance of the carbon thermometer was measured using an ac (155 cps) resistance bridge (Cryotronics Inc., Type ML100A). In order not to introduce excessive heat in the thermometer the measuring power dissipated in the resistor was kept always less than 2×10^{-9} W. Calibration of the carbon thermometer was made by measuring its resistance at the normal boiling point of He (4.2°K). A second point was obtained by pumping on the bath down to 2°K and measuring thermometer resistance and bath vapor pressure. A

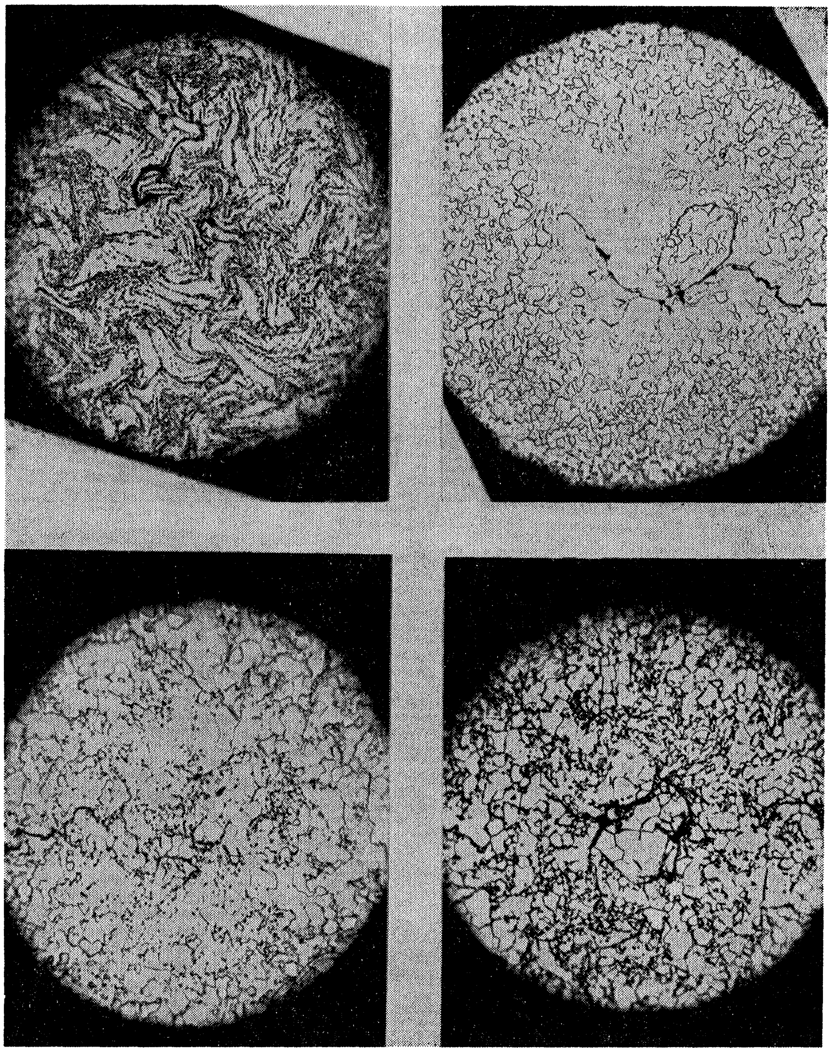

FIG. 1. Micrographs of some typical Mo-Re samples. Top left, sample A-4; top right, sample B-3; lower left, sample A-2; lower right, sample A^*-2.

third point was obtained with a liquid-hydrogen bath. This bath was one of equilibrium hydrogen and the whole procedure was similar to that used for measurements with the liquid-helium bath. The hydrogen point was computed from data reported in Hoare's book.[4] The calibrations were made with adequate exchange gas in the vacuum jacket to provide temperature equilibrium.

The relation between resistance and temperature was obtained from the three-constant formula[5]

$$\log R + K/\log R = A + B/T,$$

where A, B, and K are constants.

The temperature of the liquid-helium bath was controlled by a pneumatic device[6] which automatically maintains constant pressure.

(b) The Results

Figure 2 shows typical results for the electrical resistivity in zero magnetic field as a function of temperature for some of the 52–48% Mo-Re samples. The figure shows the superconducting transitions which are sharp and give $T_c = 11.3$°K for all the 52–48% samples. The transitions are very narrow and are of the order of the

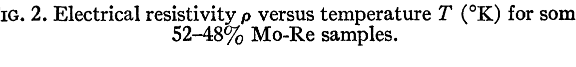

FIG. 2. Electrical resistivity ρ versus temperature T (°K) for some 52–48% Mo-Re samples.

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[4] F. E. Hoare, L. C. Jackson, and N. Kurti, *Experimental Cryophysics* (Butterworths Scientific Publications, London, 1961), p. 366.

[5] J. R. Clement and E. H. Quinnel, Rev. Sci. Instr. **23**, 213 (1952).

[6] M. M. Kreitman, Rev. Sci. Instr. **35**, 749 (1964).

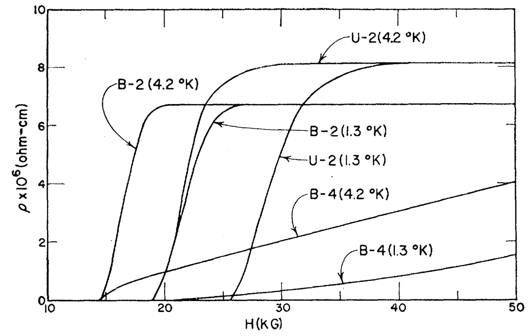

FIG. 3. Electrical resistivity ρ versus longitudinal external magnetic field H for some 60–40% Mo-Re samples.

experimental error in temperature measurement (1%). Similar data for all the 60–40% Mo-Re samples yield a common value of $T_c = 10.6°\text{K}$. It is of interest to note that within the experimental precision of measurement ($\pm 0.1°\text{K}$), T_c was found to be independent of the state of anneal.

Magnetic measurements on the same samples, which will be reported in detail subsequently, included measurements of the magnetic moment as a function of applied field and temperature. The transition temperature of the specimen was obtained from measurements of the remanent magnetization as a function of temperature. In order to obtain this curve, the specimen was cooled to 4.2°K with no trapped flux; it was then heated up to 9°K and held at this temperature while the external field was raised to 1110 G and then reduced to zero. This produced a frozen-in magnetic moment. Magnetic-moment measurements were then made in zero magnetic field as the temperature was further increased. The temperature at which the frozen-in magnetic moment became zero then identified T_c. The value obtained was $T_c = 11.1°\text{K}$ for the 52–48% samples, in agreement with the resistivity measurements.

Figure 3 shows the electrical resistivity as a function of magnetic field for some of the 60–40% Mo-Re samples at 4.2 and 1.3°K. The samples, except for B-4, show two transitions. The first transition, at which ρ first begins to show finite values, is identified with that from the bulk "mixed state" to a "surface mixed state." We assume that this transition corresponds to the Abrikosov[7] upper critical field H_{c2}. The second transition at which ρ reaches the full "normal" value is identified with that from the "surface mixed state" to the normal state, corresponding to Saint-James and de Gennes[8] H_{c3} critical field.

Similar data have been obtained for the 52–48% Mo-Re samples, all of which, except A-7, showed similar H_{c2} and H_{c3} transitions.

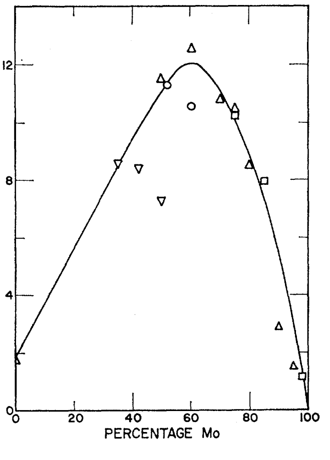

FIG. 4. Transition temperature T_c (°K) versus percentage Mo for Mo-Re alloys. □ Results of Joiner and Blaugher (Ref. 9). △ Results of Morin and Maita (Ref. 10). ▽ Results of Bucher *et al.* (Ref. 11). ○ Our results.

(c) Discussion of the Results

The values of T_c obtained in these experiments are in fair agreement with those for Mo-Re alloys of different compositions obtained by Joiner and Blaugher[9] and by Morin and Maita.[10] The previous data of Bucher *et al.*[11] do not agree well with our results, as can be seen in Fig. 4, in which the solid line is a smooth curve through our data points and those of Refs. 9 and 10.

Table II gives our evaluations from the resistivity measurements of H_{c2}, H_{c3}, ρ_{resid}. The Ginzburg-Landau[12] (GL) parameter, κ, in principle can only be calculated from these data at temperatures near T_c where the (GL) theory is valid, whereas other parameters should be introduced for $T < T_c$, as has been pointed out by Maki.[13] However, to permit comparisons with previous evaluations of κ, we have computed it in the usual way, as follows: we use first Goodman's[14] expression:

$$\kappa = \kappa_0 + 7.5 \times 10^3 \gamma^{1/2} \rho ,$$

where κ_0, the value of κ for pure substances, can be neglected in this case, γ is the Sommerfeld coefficient of the normal electronic specific heat in erg cm^{-3} deg^{-2}, and ρ is the residual resistivity in Ω cm.

γ is given by Morin and Maita[10] as equal to 10.5×10^{-4} cal deg^{-2} mole^{-1} for 52–48% Mo-Re and 10.6×10^{-4} cal deg^{-2} mole^{-1} for 60–40% Mo-Re.

It will be seen from Table II that for both alloys the fields H_{c2} and H_{c3} and κ diminish as the samples are annealed indicating an influence of stress-relief and σ phase reduction. The values of κ are in agreement with those extrapolated from the data of Joiner and Blaugher.[9]

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[7] A. A. Abrikosov, Zh. Eksperim. i Teor. Fiz. **32**, 1442 (1957) [English transl.: Soviet Phys.—JETP **5**, 1174 (1957)].

[8] D. Saint-James and P. G. de Gennes, Phys. Letters **7**, 306 (1963).

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[10] F. J. Morin and J. P. Maita, Phys. Rev. **129**, 1115 (1963).

[11] E. Bucher, F. Heiniger, and J. Muller, Helv. Phys. Acta **34**, 843 (1961).

[12] V. L. Ginzburg and L. D. Landau, Zh. Eksperim. i Teor. Fiz. **20**, 1064 (1950); V. L. Ginzburg, Nuovo Cimento **2**, 1234 (1955).

[13] Kazumi Maki, Physics **1**, 21 (1964).

[14] B. B. Goodman, IBM J. Res. Develop. **6**, 63 (1962).

TABLE II. Observed values of H_{c2}, H_{c3}, ρ_{resid} and calculated values of the Ginsburg-Landau parameter, κ, deduced as described in text.

Sample	T (°K)	H_{c2} (kG)	H_{c3} (kG)	H_{c3}/H_{c2}	$\rho_{\text{resid}}\times10^6$ (Ω cm)	κ[a]	κ[b]
U-1	4.2	21.25	33.00	1.55	8.00	4.12	5.51
U-1	1.3	27.85	42.75	1.54	8.00	4.12	5.73
*A**-1	4.2	14.35	22.20	1.53	7.80	4.02	3.72
*A**-1	1.3	17.75	...	...	7.80	4.02	3.65
*A**-2	4.2	14.60	23.75	1.62	7.80	4.02	3.79
*A**-2	1.3	19.20	...	...	7.80	4.02	3.95
A-3	4.2	14.35	27.25	1.90	5.30	2.73	3.82
A-3	1.3	18.25	37.50	2.05	5.30	2.73	3.76
U-2	4.2	19.00	28.25	1.49	8.00	3.96	5.44
U-2	1.3	25.50	37.30	1.47	8.00	3.96	5.50
B-2	4.2	14.50	19.60	1.35	7.00	3.46	4.15
B-2	1.3	19.00	26.20	1.38	7.00	3.46	4.10
B-4	4.2	14.25	...	...	6.30	3.12	4.07
B-4	1.3	20.10	...	...	6.30	3.12	4.34

[a] From $\kappa=\kappa_0+7.5\times10^3\gamma^{1/2}\rho$ (see text).
[b] From $\kappa=(H_{c2}/H_0)/F(T/T_c)$ (see text).

κ can also be calculated from the observed H_{c2} values using the Ginzburg[15] relation:

$$\frac{H_{c2}}{\kappa H_0}=\frac{2\sqrt{2}[1-(T/T_c)^2]}{[1+(T/T_c)^2]}=F(T/T_c).$$

H_0 has been evaluated from the formula

$$H_0=2.42\gamma^{1/2}T_c,$$

which follows from the BCS theory,[16] and H_0 is found to be 1.80 kG for the 52–48% alloy and 1.69 kG for the 60–40% alloy. The evaluations of κ by this method are shown in Table II.

Comparing the theoretically predicted value of $H_{c3}/H_{c2}=1.69$, given by Saint-James and de Gennes,[8] with the ones given in Table II it can be seen that there are discrepancies of about ±15%. The discrepancies could be explained by uncertainty in interpreting the exact values of H_{c3} and also by the influence of impurities in the samples.

For samples *A**-1, *A**-2 at 1.3°K, there is difficulty in estimating H_{c3} which could be interpreted as due to the existence of a "surface mixed state" up to higher fields (45 kG). This effect could be due to the two phases, β and σ, having different critical fields, and this might show up in surface effects rather than in bulk effects. This assumption is supported by the fact that the behavior is not observed in the single-phase (60–40% Mo-Re) samples.

Samples *A*-7 and *B*-4 (see Fig. 4) showed a completely different behavior in the presence of magnetic fields. They had a very broad "surface mixed state," which might be due to precipitation of impurities during their long annealing. Similar transition curves were obtained by Joiner[17] in In+Al+Sn alloys, and he attributes them to precipitations. This behavior seems not to be due to the secondary phase σ because the single phase alloy (*B*-4) also shows similar behavior. *B*-4 however was annealed under the same conditions as *A*-7.

4. THERMAL CONDUCTIVITY

(a) Experimental Arrangements

The samples were in the form of single wires, all of 52–48% Mo-Re of the same diameter, 0.024 cm, and 3 cm long, at different states of anneal, as specified in Table I. One end of each sample was thermally anchored to a copper post at the liquid He^4 bath temperature, and the other end carried an electrical heater. In order to assure good electrical and thermal contact between sample and copper post and between sample and heater, platinum foils were soldered with Wood's metal to the sample ends. The upper platinum foil was soft soldered to the copper post and the lower one to the heater.

The sample ends and the locations where carbon resistors were attached were ultrasonically tinned with indium. Two Allen-Bradley carbon resistor thermometers (nominal room temperature resistance 200 Ω, $\frac{1}{2}$ W) had one of their ends soldered to the sample with indium, and the other end soft soldered to No. 36 Evanohm wire. Evanohm wire was chosen for leads since it was found[18] to have zero magnetoresistance effect. The heater was double wound on a No. 18 copper wire, which had its insulation removed, for a better

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[15] V. L. Ginzburg, Zh. Eksperim. i Teor. Fiz. **30**, 593 (1956) [English transl.: Soviet Phys.—JETP **3**, 621 (1956)].

[16] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).

[17] W. C. H. Joiner, *Conference on Physics of Type II Superconductivity, Cleveland* (Western Reserve University, Cleveland, Ohio, 1964), p. IV-75.

[18] E. Lerner and J. G. Daunt, Rev. Sci. Instr. **35**, 1069 (1964).

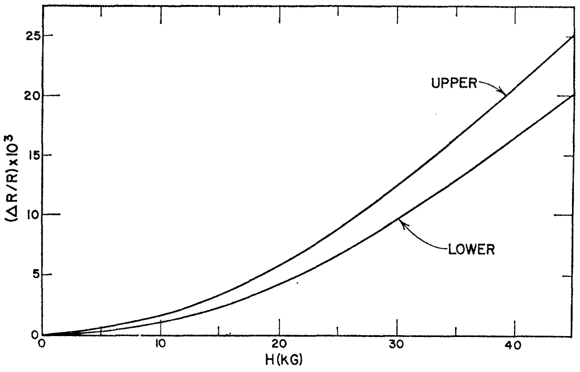

FIG. 5. Magneto-resistive effect in carbon resistance thermometers at 4.2°K.

thermal contact. The heater had 1575 turns on 37 layers of No. 44 Advance wire (73.5 Ω/ft) and a resistance, at room temperature, of about 5700 Ω.

The sample, heater and carbon resistor thermometers were enclosed in a vacuum jacket, which was surrounded by liquid helium and arranged in such a way that a longitudinal magnetic field of intensity up to 50 kG could be produced around the sample by a superconducting solenoid whose center coincided with the sample's center. The current to the solenoid was supplied by a programmable power supply (Cryotronics Inc., Model ML700). For a more detailed analysis of the thermal conductivity in the low-field region, a 6-V battery and rheostats were used in place of the power supply.

A 1000-Ω Evanohm resistance was placed at the bottom of the helium Dewar and 6 V applied to it, in order to stir the bath.

Current was supplied to the heater by a 6-V battery and the voltage across the heater was measured by a standard potentiometric circuit. The current was monitored by a 1000-Ω standard resistor (Leeds & Northrup Model 4035B). The carbon resistance thermometers gave the temperature of the respective points where they were attached. As mentioned previously, their resistance was measured with an ac bridge, with measuring powers less than 2×10^{-9} W. They were calibrated as described previously. In these experiments corrections also had to be made for the magnetoresistance effect, since the measurements were made in the presence of magnetic fields. In order to correct the results for this effect, isothermal measurements were made at 4.2°K for each resistor. The thermometers were in direct contact with the liquid helium bath. Figure 5 shows the effect for each thermometer.

The magnetoresistance effect observed is proportional to H^2 and can be expressed by $[(R-R_0)/R_0]=aH^2$, where $a_1=1.48\times10^{-5}$ kG^{-2} for the upper thermometer and $a_2=1.04\times10^{-5}$ kG^{-2} for the lower one. These values are in good agreement with the data of Clement and Quinnel[5] ($a=1.12\times10^{-5}$ kG^{-2}) and, therefore, Clement's formula was used in the corrections; his formula is

$$(R-R_0)/R_0=A\times10^{-5}T^{-3/2}H^2,$$

where R is the thermometer resistance at the field H and R_0 is the resistance in zero magnetic field. For the thermometers used in this experiment $A_1=12.73$ for the upper thermometer and $A_2=8.96$ for the other one.

(b) The Results

Figures 6, 7, and 8 show the thermal conductivity as a function of external magnetic field for different samples and at different temperatures.

For the unannealed sample (U-1) it seems that thermal conductivity is independent of magnetic field for a constant temperature as shown in Fig. 6.

For the annealed samples (A-1, A-2, and A-3) a sharp transition occurs near 500–600 G, where the superconducting-mixed state transition (H_{c1}) presumably occurs. The magnetic measurements on U-1 indicated an H_{c1} value, at for example 4.2°K, of 660 G.

Samples A-1 and A-2 showed a peculiar effect. After measuring the thermal conductivity as a function of magnetic field H at 4.2°K [Curve (a), Fig. 7], in order to calibrate the thermometers the temperature was

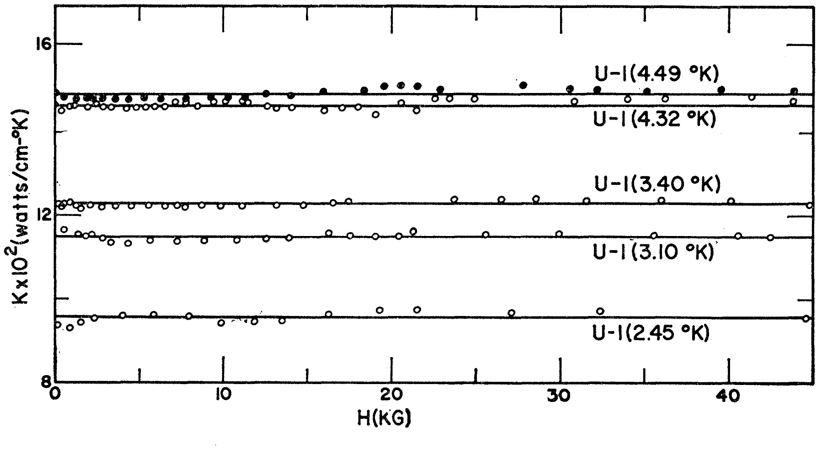

FIG. 6. Thermal conductivity K of sample U-1 versus external magnetic field H at various constant temperatures, as marked.

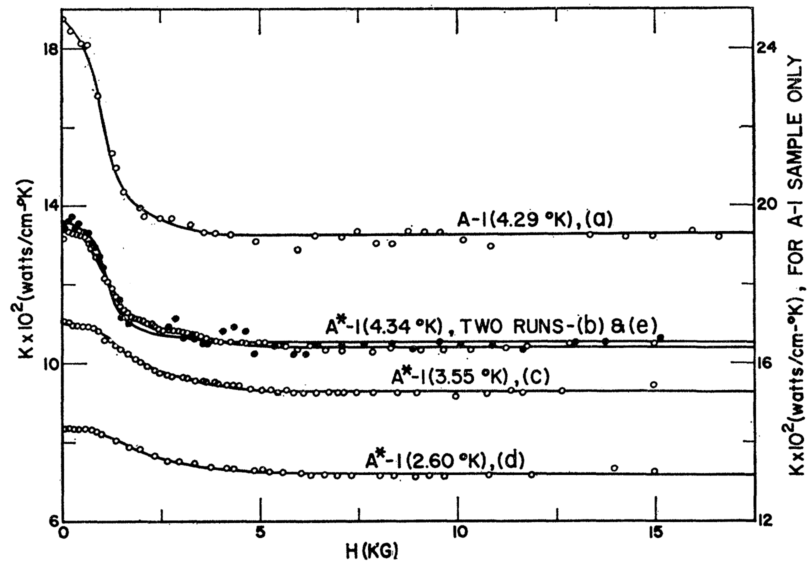

FIG. 7. Thermal conductivity K of sample A-1 and A*-1 versus external magnetic field H at various constant temperatures, as marked.

lowered to 1.3°K. The specimen was then allowed to warm up slowly to room temperature, at which it was maintained for ten days. Then new low temperature measurements were made and curves (b), (c), and (d) of Fig. 7 were obtained. To confirm these results, further measurements were made at 4.2°K nine days later and curve (e) in Fig. 7 was obtained in good agreement with curve (b).

Since sample A-2 was annealed under the same conditions as A-1, with the difference that the former was quenched in water and the latter was cooled slowly, measurements on A-2 were made. Figure 8 shows the results obtained for this sample. In order to check if the magnetic field was responsible for the effect observed in A-1, the field at sample A-2 was raised up to 48 kG at 4.2°K twice and the same values of the thermal conductivity for A-2 were obtained. The temperature was then lowered, and after reaching 1.3°K the sample chamber was taken out to room temperature and allowed to warm up quickly. This was done in order to check if the observed effect was due to a slow warm-up of the sample, since A-1 stayed inside the Dewar during the warm-up and came to room temperature only after 3 or 4 days. New measurements were made several days later on A-2 and again, as in the case of A-1, lower values for thermal conductivity were obtained.

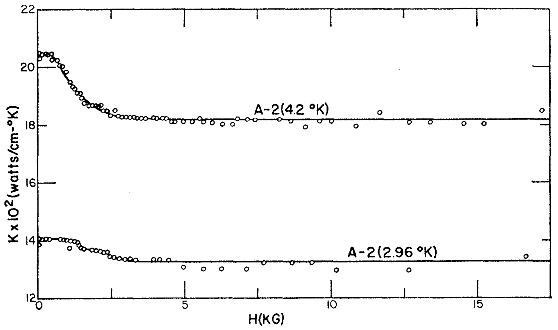

FIG. 8. Thermal conductivity K of sample A-2 versus external magnetic field H at 4.28°K and 2.96°K.

This temperature cycling effect is probably connected with the fact that these samples were annealed at about 1250°C. At this temperature the alloy is close to the phase boundary between the regions of single β phase and the region of β and σ phases. Therefore, it could happen that after temperature cycling the σ phase recrystallized and changed the alloy's properties. Indeed an increase of σ-phase content in the samples was observed by comparing microphotographs taken before and after measurements were made (Table I). In order to signify the occurrence of this effect in the various samples, the code letter (see Table I) of each sample number is marked with an asterisk (e.g., A*-1).

Typical curves giving the thermal conductivity values of samples U-1 and A*-2 for $H=0$ as a function of temperature are given in Fig. 9.

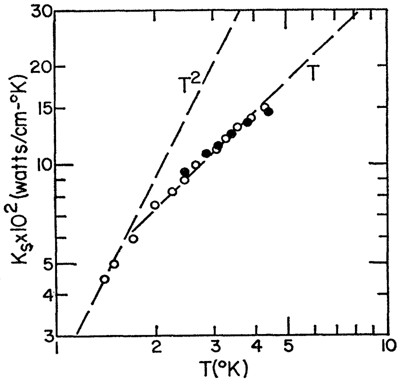

FIG. 9. Thermal conductivity K of samples U-1 and A*-2 for $H=0$ as a function of temperature T(°K). Points marked ● give U-1; points marked ○ give A*-2. The broken lines show theoretical evaluations for K proportional to T and to T^2.

(c) Discussion of Thermal-Conductivity Data

The data referred to in Sec. 4(b) and partially illustrated by the graphs of Figs. 6, 7, and 8 indicate that:

(1) The absolute-value thermal conductivity K at any given temperature increased after annealing. However, owing to the scatter in the data and to the irreversible changes accompanying the low-temperature thermal cycling process [see Sec. 4(b)], it is not possible to make detailed comparisons of the effects of annealing. It appears, however, that K increases as the σ content decreases, both for the normal and super states.

(2) For the unannealed sample, U-1, no difference in K was observed when the sample was changed from the super to the normal state by application of an external magnetic field at constant temperature. This state-independent thermal conductivity is an unusual feature. A somewhat similar occurrence has been observed by Mendelssohn[19] in a Ta-Nb alloy in the temperature range 2.5 to 4.2°K.

(3) For the annealed samples, a sharp falloff in the K values in increasing magnetic fields during isothermal measurements occurs at the H_{c1} values, as has been observed previously, for example, by Dubeck *et al.*[20] with In-Bi alloys. (The measured H_{c1} values obtained in magnetic-moment measurements on these samples will be reported in a subsequent paper.) In sample A^*-3 with minimum σ phase content, a shallow minimum in the K-versus-H curve was observed to occur in the mixed phase region, again as has been observed by Dubeck *et al.*[20] The graphs on Figs. 7 and 8 for samples A-1, A^*-1, and A-2 may also be interpreted as showing a very shallow minimum. It is considered that our results are to be explained on the same basis also, being due largely to decreasing lattice conductivity K_g in going from the super to the normal state.

(4) For the annealed samples $K_n<K_s$ at all temperatures of observation. This result is in marked contrast with those of Radhakrishna and Nielsen[21] on dilute Nb-Zr alloys who found $K_n>K_s$ over the entire temperature range. Our observation is not unusual in superconducting alloys,[22] particularly those with a significant lattice contribution to K.

At sufficiently low temperatures the Lorenz number L_0 defined by $L_0=\rho_0 K/T$, should be equal approximately to 2.45×10^{-8} W Ω/deg^2 provided the thermal conduction is dominantly electronic in character. Our data of ρ_0 and K indicate that L_0 is very much higher than the value expected for electronic conduction and in fact indicates that the thermal conductivity is largely by phonons.

In an attempt to estimate the phonon scattering mechanisms dominant in our Mo-Re samples, we have investigated the temperature dependence of K_n and K_s. Figure 9, for example, plots logarithmically K_s versus T for samples U-1 and A^*-2 and it will be seen that here, as for other samples, no simple function of temperature is applicable to the results. At the lowest temperatures phonon scattering by external and grain boundaries gives theoretically a T^3 dependence of K_{phonon}; scattering by electrons and by dislocations gives T^2 with, in general, the electron-scattering process being dominant. As the temperature is raised, other scattering mechanisms become more important, as, for example, point defect scattering. This will cause K_{phonon} to pass through a maximum value, subsequently decreasing in value as T increases. By comparison with the broken curves of Fig. 9, which show theoretical T^2 and T dependence of K, it is clear that at the lowest temperatures our results indicate a T^2 dependence of K and show that as T is increased other scattering mechanisms with lower T dependence are becoming significant.

With this interpretation of our thermal conductivity results, namely that K is dominantly phonon conduction, the change in K in the annealed samples with magnetic field can be understood as follows. For $H=0$, and at sufficiently low temperatures, the thermal conductivity is due mainly to phonons with dislocation, grain boundary (and β-σ phase boundary), and possibly stacking fault boundary scattering processes being dominant. When H reaches the value H_{c1} (about 600 G at 4.2°K for our 52–48% samples), phonon-electron scattering begins and K shows a decrease. Between H_{c1} and H_{c2}, the samples are in the mixed phase and the phonon-electron scattering continues to increase until the sample is all normal. Since electron conduction K_e plays a negligible role in the total observed conductivity, the rise in K_e in the mixed phase (see, for example, Dubeck *et al.*[20] for evidence of this) contributes no measurable addition to K_{total}. The value of K, therefore, in general does not show a minimum as H increases.

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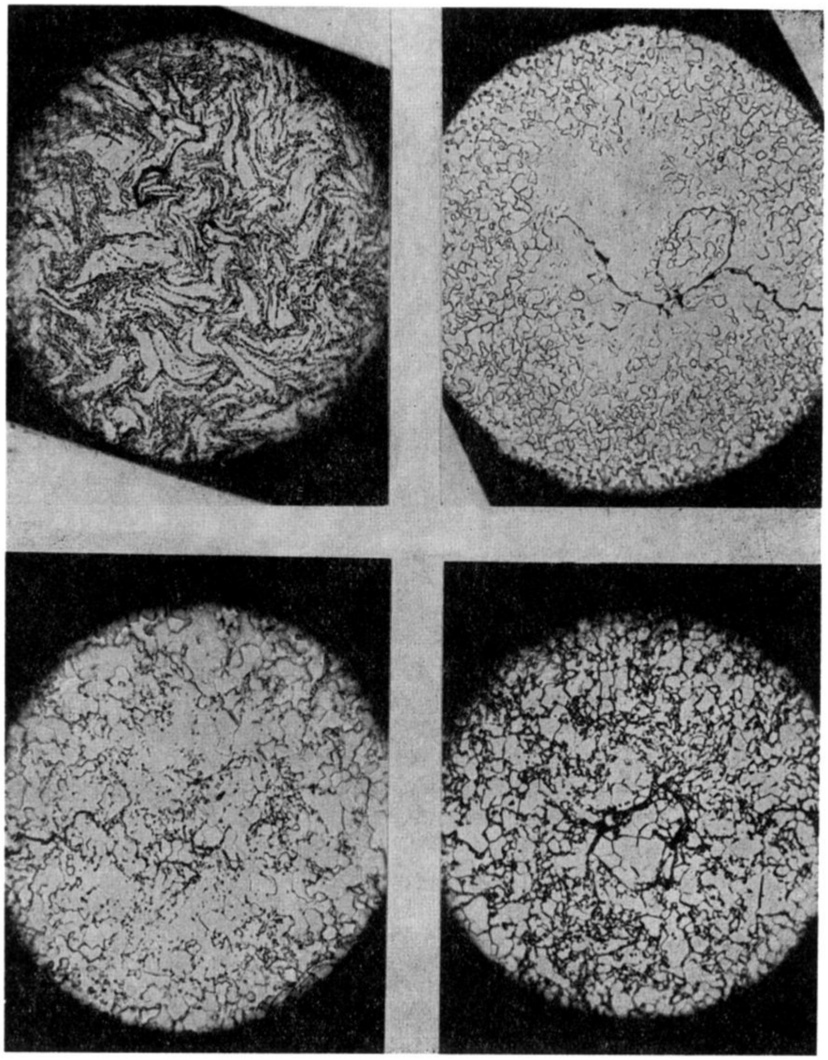

Fig. 1. Micrographs of some typical Mo-Re samples. Top left, sample *A*-4; top right, sample *B*-3; lower left, sample *A*-2; lower right, sample *A**-2.