$K_1 = 4.3\times10^6$, $K_2 = 1.2\times10^6$ ergs cm^{-3}. The torque curve calculated from these constants, using

$$L = -(K_1+K_2)\sin 2\theta + \tfrac{1}{2}K_2\sin 4\theta, \tag{15}$$

derived from Eq. (5) with $K_3 = K_4 = 0$, is shown by the solid line in the figure. The values previously derived from the magnetization curves of Honda and Masumoto are $K_1 = 4.0\times10^6$, $K_2 = 2.0\times10^6$. A negligible value of K_3 is suggested by the agreement between the corrected torque data and the torques calculated using only K_1 and K_2.

Measurements on Specimen 6, a disk cut parallel to $(00\cdot1)$, were made to estimate the magnitude of K_4. A slight 6θ component was detected, corresponding to $K_4 = +3000$ ergs cm^{-3}. This is about $10^{-3}K_1$ and is considered negligible and uncertain.

The field necessary to saturate cobalt at right angles to the hexagonal axis is calculated to be

$$H_s = (2K_1 + 4K_2)/I_s = 9500.$$

I am indebted to Mr. R. C. Sherwood for preparation of the specimens from the crystals, and to Mrs. E. F. Tilden and Mr. A. J. Williams for assistance with the measurements. My appreciation is also due to Miss M. C. Gray for evaluating the constants used in calculating magnetostriction as dependent on field strength, and to Mrs. G. J. Rowe for setting up and operating the analog computer used in this evaluation.

PHYSICAL REVIEW VOLUME 96, NUMBER 2 OCTOBER 15, 1954

Superconductivity of Vanadium at 24 000 Mc/sec

C. J. GREBENKEMPER
Naval Research Laboratory, Washington, D. C.
(Received June 4, 1954)

The high-frequency resistance of vanadium was measured at frequencies in the vicinity of 24 000 Mc/sec in both the normal and superconducting states using resonant cavity techniques.

The normal conductivity was not affected by the "anomalous skin effect" as much as the "soft superconductors." The inner surfaces of the cavities were mechanically polished to a good surface finish. The normalized surface resistance extrapolated to absolute zero yields a value of 0.007 times its initial resistance.

INTRODUCTION

SUPERCONDUCTIVITY of vanadium is of interest because this metal belongs to the class of "hard superconductors." Most of the metals in this class do not exhibit a sharp transition between the normal and superconducting state. The "soft superconductors" almost always exhibit an extremely sharp transition. The behavior of vanadium at high frequencies is of interest since very little work has been done on the "hard superconductors" at high frequencies. McLennan[1] and co-workers investigated tantalum at 10 Mc/sec many years ago and found an abnormally high resistance.

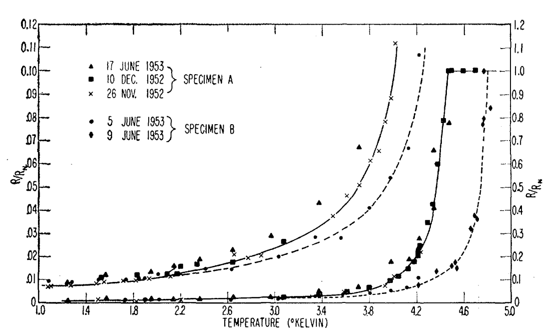

FIG. 1. Surface resistance of vanadium in superconducting state.

APPARATUS AND TECHNIQUES

The present work was done at frequencies near 24 000 Mc/sec. The method used was to measure the electric Q factor of a resonant cavity and from these measurements calculate the surface resistance. The method of Q measurements and techniques[2] are described in an earlier paper and will not be discussed here. In the earlier paper the cavities operated in the TE_{111} mode, in this particular case the TE_{114} mode is used. The ratio of diameter to length is 1.0. The cavity was formed from two pieces that were machined from a vanadium ingot. The junction of the two parts was along a plane which has no transverse currents flowing. The interior surface of the cavity was polished mechanically to a good finish. The polishing compounds used were: first, No. 275 carborundum, then No. 400 corborundum and the final polishing was done with Linde "b" polishing compound using distilled water and aerosol as a wetting agent. Because of the difficulty of attaching vanadium to standard wave guides a special holder was constructed of brass. A gold O ring was used to seal the two parts of the holder. This arrangement was satisfactory in the normal helium region.

[1] McLennan, Burton, Pitt, and Wilhelm, Proc. Roy. Soc. (London) **136**, 52 (1931).

[2] C. J. Grebenkemper and J. P. Hagen, Phys. Rev. **86**, 673 (1952).

In the helium II region "superleaks" were troublesome.

The vanadium used in the present experiments was obtained from the Electro Metallurgical Division of the Union Carbide and Carbon Company and was of high purity. Table I gives the purity analysis of the metal. The ingot was not perfect since a number of blowholes were present. These were probably due to gases trapped in the melt. Hardness tests were conducted on a sample of the metal and yielded a Vickers hardness number of 164. After the sample was annealed at 1000°C for several hours at a residual vacuum of 4×10^{-6} mm Hg the hardness number rose to 172. From this it would appear that annealing can be detrimental unless carried out under an extremely high vacuum.

SUPERCONDUCTING STATE

A plot of R/R_n *vs* temperature is shown in Fig. 1. It can be seen from the curves that the two specimens do not have the same transition temperature even though the specimens were formed from adjoining sections of the ingot. The specimen was immersed in liquid helium at the bottom of the flask as described previously.[2] The temperature of the bath was controlled by adjusting the pressure of the helium vapor in the flask. Care was used in raising the bath temperature so that equilibrium conditions would prevail. To obtain temperatures above 4.2°K, current is passed through a resistor, which was installed underneath the cavity to raise the vapor pressure above atmospheric pressure. The temperatures were determined from vapor pressure measurements using the 1948 temperature scale.

TABLE I. Purity analysis of the metal.

Elements	Amount of impurities in percent (by weight)
O_2	0.063–0.068
N_2	0.030
H_2	0.0016–0.0024
Cr	0.05
Spectro chemical analysis	
Si	0.01–0.1 percent
Mn	0.01–0.1 percent
Fe	0.01–0.1 percent
Al	0.01–0.1 percent
Ti	0.001–0.01 percent
Cu	0.001–0.01 percent

The consistency of measurements for a given specimen was quite good. The possibility of the lack of equilibrium conditions was investigated. The bath temperatures were raised and lowered in the usual way and there were no marked discrepancies for a given specimen. In the final analysis it appears that the difference in the transition temperature for the two specimens is real and must be ascribed to the difference in internal strains in the ingot. After the measurements were completed the cavities were disassembled and hardness tests were conducted on each specimen. It was found that specimen B was considerably softer than specimen A. Specimen A had a Vickers hardness number of 192 and specimen B the Vickers hardness number was 170. This difference in the transition temperatures due to the differences in hardness is in agreement with the work of Wexler *et al.*[3]

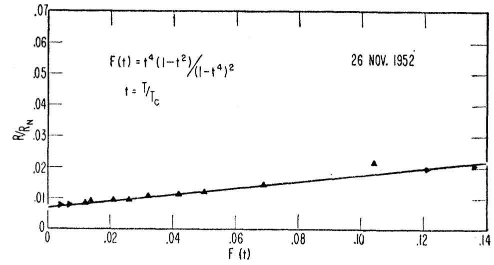

FIG. 2. Linear plot of the low-temperature resistance of vanadium in the superconducting state.

NORMAL STATE

Q measurements in the normal region were determined by band width measurements in addition to decrement measurements. The decrement method is not too precise for the low values of Q encountered here. The two methods did not disagree by more than 10 percent however. The normal conductivity, which is given in Table II, was not affected as much by the anomalous skin effect as the "soft superconductors." The calculated Q value for this particular cavity was 13 900 if one used the results of Wexler for the low-temperature conductivity of vanadium. The measured value was quite close to this figure. For the "soft superconductors" the anomaly is much greater, the measured Q value for "soft superconductors" being about one-fifth the calculated Q, using classical theory. A possible explanation of the smaller anomalous skin effect in vanadium is that the electron has a shorter mean-free path in vanadium than in tin. This would appear plausible, since, in transition metals with incomplete "d" shells, a much larger scattering probability exists, hence a shorter mean-free path is expected with this material as compared with metals with closed cores.[4]

When R/R_n is extrapolated to absolute zero, shown in Fig. 2, a residual resistance of 0.7 percent of the resistance at the transition is obtained. For tin with a

TABLE II. EXPERIMENTAL RESULTS

Metal	Surface conductivity $ohms^{-1}$	$A(\omega)$	R/R_n extrapolated to absolute zero	Frequency Mc/sec
Tin	80	0.25	0.002	24 080
Vanadium	13.8	0.11	0.007	23 970

[3] A. Wexler and W. S. Corak, Phys. Rev. **85**, 85 (1952).

[4] See N. F. Mott and H. Jones *The Theory of the Properties of Metals and Alloys* (Oxford University Press, London, 1936), pp. 247 and 266.

good polished surface[5] this value of the residual resistance is 0.2 percent; this is shown in Fig. 3. Theoretically, the resistance should vanish at absolute zero if all the normal electrons are converted into superconducting electrons.

If the normalized surface resistance of vanadium is plotted against tin using $f(T)$ as a parameter, Fig. 4, a linear relationship is found to exist. Vanadium, a "hard superconductor," is very similar in its manner of changing resistance with temperature to the "soft superconductors" in the superconducting state. It is quite possible that with a high purity strain free specimen that had a good surface finish the residual resistance at absolute zero would approach zero. This work appears to support Wexler's suggestion that the internal stresses due to atoms located in interstitial positions in the lattice markedly affect the superconducting properties. The transition temperature for the softer specimen compares more favorably with Wexler's value of 5.13°K than the earlier value of Meissner and Westerhoff[6] of 4.3°K.

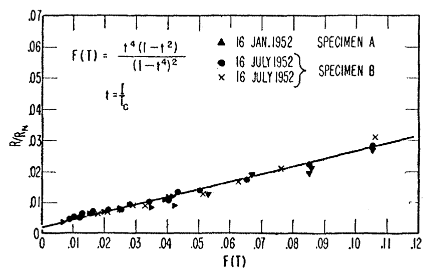

FIG. 3. Linear plot of the low-temperature resistance of tin in the superconducting state.

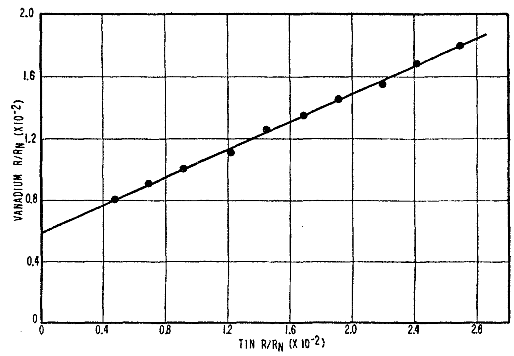

FIG. 4. Linear plot of the normalized surface resistance of vanadium *vs* tin with $f(T)$ as a parameter.

ACKNOWLEDGMENTS

The author is indebted to Dr. J. P. Hagen for his frequent advice and discussions. Special thanks are due to A. R. Donaldson, of the Metallurgy Division, for his advice on polishing techniques and the hardness measurements and to D. I. Walter of the Metallurgy Division for the analysis of the impurities in the vanadium.

[5] C. J. Grebenkemper and J. P. Hagen, Proceedings of the Schenectady Cryogenics Conference, 1952 (unpublished).

[6] W. Meissner and H. Westerhoff, Z. Physik **87**, 206 (1934).