Thermochimica Acta, 103 (1986) 83—88
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

SUSCEPTIBILITIES OF SUPERCONDUCTING VANADIUM MEASURED FOLLOWING THE FARADAY METHOD

A. VAN DEN BOSCH and J. VANSUMMEREN
Materials Physics Department, S.C.K./C.E.N., B-2400 MOL (Belgium)

ABSTRACT

An apparatus for measuring static magnetic susceptibilities, based on a sensitive vacuum microbalance, has been used for studying the magnetic behaviour of small superconducting samples in small gradients of low fields. Forces on superconducting vanadium discs, cooled in fields $\lesssim$ 10 mT, have been measured at 3 K following the Faraday method. It is observed that the sum of the magnitudes of the susceptibilities, related to i) the Meissner-Ochsenfeld effect and ii) the frozen-in currents, is equal within experimental error to the magnitude of the susceptibility at the induction of the moments at 3 K by generating similar fields.

INTRODUCTION

A vacuum microbalance, with a sensitivity about 10^{-9} N, is the striking part of an apparatus for measuring static magnetic susceptibilities on small solid samples following the Faraday method (ref.1). The low temperature performances of the apparatus have been described previously (ref.2). Forces on a thin superconducting vanadium disc, cooled in fields $\lesssim$ 10 mT, have been measured at 3 K. Results obtained in this way have been analysed for sample moments consisting of two parts: an induced one which is proportional to the field and a permanent one. The susceptibility of the sample has been shown: i) to be independent of the magnetic fieldstrength in the range where $\mu_0 H < 8$ millitesla; and ii) to be independent of the permanent moment which had been generated in the sample by cooling it in an applied magnetic induction field of 12 mT. The permanent moment was shown to be reproducible to better than 0.5 per cent. The aim of the present paper is to report on the behaviour of the generated permanent moment and on its relation with the Meissner-Ochsenfeld effect.

EXPERIMENTS AND RESULTS

The susceptibility measurements, for the present study, have been carried out on a thin 3.00 mm diameter disc of very pure zone-refined vanadium. The sample stems from one of the cold-rolled 0.2 mm thick foils of the batch used in reference (3). The sample S1 has been punched out of the foil as received.

0040-6031/86/$03.50

Its mass m = 8.22 mg. With $\rho = 5.96 \times 10^3$ kg m^{-3}, the density of bulk vanadium, the average sample thickness is calculated to be 195 μm. After the magnetic measurements having been carried out, sample S1 has been heat treated for one hour at 600°C in a vacuum < 10^{-3} Pa. The sample then is labelled S2.

During the whole experiment, the vanadium continuously lies on the balance pan for the force measurements. The pan hangs in the dewartail on which a small ironless coil is mounted. The latter generates a magnetic field with a gradient at the sample place. For the present study all experiments have been carried out with the sample at the same position on the coil axis, P = 11.0 mm in the copper-coil/sample-pan situation as described in reference (2). The applied field at the sample, therefore, is proportional to the coil current I. It is:

$$H = H_1.I = 8.00 \times 10^3 \times I \ (Am^{-1}) \qquad (1)$$

At the same place the gradient of the applied induction field is also proportional to I, i.e.:

$$G = \mu_0 \ (dH/dz) = G_1.I = - 0.464 \times I \ (Tm^{-1}) \qquad (2)$$

with μ_0 the free space permeability. Before starting the series of experiments, to be carried out on a chosen sample, the latter is oriented with its flat plate perpendicular to the applied field.

For each experiment the persistent currents are generated in the vanadium disc in the following way. The sample temperature is brought to 7 K and the coil current is set to I_c. The disc is cooled to 3 K afterwards. Time is spent for allowing the balance to settle for low noise and high sensitivity. The coil current intensity then is brought down to zero and the related force change

$$F_c = F_I - F_0 \qquad (3)$$

is read. Subsequently, force measurements are carried out for coil currents I_m = 60.0 (± 0.1) mA in a chopping mode alternating the current direction. Reversing the direction allows for differentiating between the induced moment and the permanent one. The measured sample force in the system is:

$$F = m(\chi H+P)G \qquad (4)$$

where χ is the susceptibility per unit of mass and P the permanent dipole moment per unit of mass. Because H and G are proportional to the measuring current I_m the force fraction due to χ, F_A, is proportional to I_m^2 while that due to P, F_B, is only proportional to I_m. Consequently, the force can be expressed as:

$$F = F_A + F_B = AI_m^2 + BI_m \qquad (5)$$

The values of A and B are calculated, using the balance output voltage V and the balance constant $C = 5.14 \times 10^5$ VN^{-1}, by:

$$A = (V(+) + V(-))/(2I_m^2C) \qquad (6)$$

$$B = (V(+) - V(-))/(2|I_m|C) \qquad (7)$$

The signs (+) and (-) refer to the polarity of the coil current I_m.

The susceptibility $\chi = A/(mH_1G_1)$ (8)

The persistent moment P is related to χ_B by:

$$\chi_B = P/(H_1.I_c) = B/(mH_1G_1I_c) \qquad (9)$$

The susceptibility $\chi_M = F_c/(mH_1G_1I_c^2)$ (10)

Also it has been calculated, for each experiment:

$$\Sigma = \chi_M - \chi_B = -(|\chi_M| + |\chi_B|) \qquad (11)$$

Such an experiment, from the cooling of the vanadium in the field of the coil current I_c to the computation of χ, χ_B, χ_M and Σ has been carried out for each sample for the series of current intensities I_c = + 0.200 A, + 0.400 A, + 0.600 A, + 0.800 A, + 0.900 A, + 0.700 A, + 0.500 A and + 0.300 A, in the order given.

The values of χ, χ_B and Σ of sample S2 are plotted versus I_c in Figure 1. The averages of χ, Σ, χ_B, χ_M and their sigmas are given in Table 1 for both samples. In the same table the upper- and lower-limits, of the temperatures at which the χ and χ_B measurements on the sample have been carried out, are reported too. It appears that the values of χ_M, although small, are reproducible.

DISCUSSION

In all experiments considered here the susceptibilities χ are observed to be negative, which means that the superconductors behave as diamagnetic materials. The small values of σ indicate that the values of χ mainly consist of a constant term $\bar{\chi}$ on which small deviations are superposed. The observation, that χ seems to be a sample constant, is consistent with the statement made in reference (2). In that reference only the extreme cases, I_c = 0.0 and I_c = 0.9 A, have been considered. The present work extends the statement to hold also for I_c values in between.

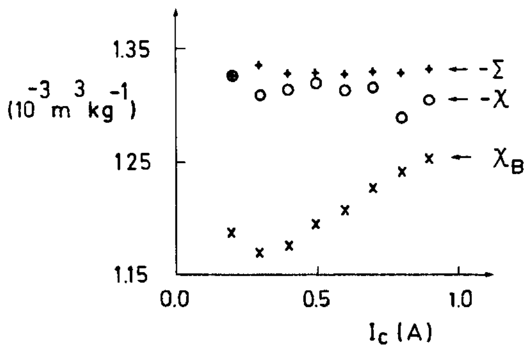

Fig. 1. The susceptibilities of sample S2.

TABLE 1

	Average susceptibilities (m^3kg^{-1})				T(K)
Sample	$-\bar{\chi}\cdot10^3$ $\sigma\cdot10^3$	$-\bar{\Sigma}\cdot10^3$ $\sigma_\Sigma\cdot10^3$	$+\bar{\chi}_B\cdot10^3$ $\sigma_B\cdot10^3$	$-\bar{\chi}_M\cdot10^3$ $\sigma_M\cdot10^3$	T_{up} T_{low}
S1	1.334 <0.010	1.346 <0.002	1.329 <0.005	0.017 <0.005	3.0 2.8
S2	1.313 <0.012	1.329 <0.004	1.208 <0.031	0.121 <0.031	3.2 3.0

The present study concerns more the magnetic moments which are generated in the vanadium discs by cooling them, in a small applied magnetic field H, from above to below the critical temperature T_c. The experimental results are analysed to show that, during the cooling in the field, a minor flux fraction is expelled while the major flux part is retained in the sample.

The force change, at the reduction of I_c after the cooling, was measured accurately when the balance had stabilized during the stabilization of the measuring temperature at 3 K. All the χ_M values also were observed to be negative. Upon cooling in a constant field the superconductor became more diamagnetic, as expected from the Meissner-Ochsenfeld effect. When the coil current intensity I_c is reduced to zero the gradient G of the field is reduced to zero too so that no forces are exerted by the coil on possible persistent currents. The F_c forces, therefore, are attributed to the Meissner-Ochsenfeld effect.

When a small measuring current I_m is sent through the coil, thus creating a gradient, the resulting χ_B values all are positive. It expresses that, as far as the force fraction F_B is concerned, the samples are attracted by the coil when the current direction of I_m and I_c are the same. They are repelled, however, when their signs are different. The observation is understood on the model in which currents are induced, in the sample, in a direction as to "oppose" the change in magnetic flux through the disc. In the "B" case the disc is not superconducting when the field has been put on by I_c. The generated sample currents, therefore, died out. After the cooling, however, the vanadium is superconducting. At the field lowering the generated currents then are opposing the flux decrease. They are not dying out anymore. In terms of an effective ring current, its direction in the case of χ_B is opposite to that at the measurement of χ. Indeed, in the "A" situation, the disc is superconducting before the field is applied by I_m, so that the persistent superconductive currents in the case of χ are opposing the flux increase.

When the vanadium is superconducting, the currents persist as long as the applied field remains unchanged. The resulting sample dipole moment, therefore, is persistent too. The observation that, for a sample cooled through I_c in an applied field $\chi_B \neq 0$ learns that the dipole moment is not free to change direction in the disc. Depending on the sign of I_m the dipole behaves as a paramagnetic- or as a diamagnetic-entity.

The deviations:

$$d_B = \chi_B - \bar{\chi}_B \qquad (12)$$

are small. The largest relative deviation, $|d_{B,max}/\bar{\chi}_B| = 0.038$, is observed to occur for sample S2. The deviations d_B for S2 are shown in Fig. 1 to be correlated with I_c. It means that they can not be considered as due to randomly distributed measuring errors. A similar systematic behaviour of:

$$d_M = \chi_M - \bar{\chi}_M \qquad (13)$$

versus I_c is observed too. Moreover, d_M is about equal to d_B for all values of I_c, so that for $\Sigma = \chi_M - \chi_B$ the sigma value:

$$\sigma_\Sigma = (\sum_1^n d_\Sigma^2/(n-1))^{0.5} \qquad (14)$$

is an order of magnitude smaller than σ_B or σ_M. The deviations d_Σ do not show a correlation with I_c so that they can be considered as due to random measuring errors. The value of σ_Σ, 4×10^{-6} m^3kg^{-1}, can be considered as a high figure for the σ value on the measurement of χ_B. It results in a variation coefficient $\zeta_B \leq 100.\sigma_\Sigma/\bar{\chi}_B \leq 0.34$ % which is a measure for the precision on χ_B. Consequently, the measured differences in χ_B are significant.

In relation to the constant Σ are the values of $-\chi_B$ complementary to those of χ_M. The moment retained in the sample after cooling, is complementary to the moment, due to flux expulsion by the Meissner-Ochsenfeld effect at the cooling in the applied field. The complementary behaviour is understood when on the one hand the flux fraction $\alpha\phi$, expelled following the Meissner-Ochsenfeld effect, yields values for χ_M, while on the other hand the retained flux part $(1-\alpha)\phi$ results in values for $-\chi_B$, both with the same proportionality constant. The latter constant is observed to be the same, within experimental error, as that for inducing moments at 3 K. The observation broadens the meaning of the statement made in reference (2). Not only χ but also $\Sigma = \chi$ is a sample constant.

In the expression $\chi_M = \alpha\Sigma$ and $-\chi_B = (1-\alpha)\Sigma$ one has $\alpha \ll 1$ in all experiments. Only the smaller part of the flux was expelled from the sample. In the flat discs the deviations from the ideal plan parallel surfaces may cause flux trapping. It therefore becomes difficult to predict the value of α. This does not mean that α is not reproducible. Indeed, as part of the measurements have been carried out with an I_c value smaller or larger than the previous I_c value, the smooth evolution of χ_B versus I_c, as shown in Fig. 1, is a good indication for the reproducibility of the measurements and for the independence of the results from the previous measurements. In every sample α is observed to depend on I_c, indicating that field dependent trapping occurs. The value of α of S1 for I_c = 0.7 A was increased, by the heat treatment, by a factor of 4. The maximum of α occurred in S1 at I_c = 0.7 A in S2 at I_c = 0.3 A. The flux expulsion clearly depends on the heat treatment.

The susceptibility value i.e. the sample constant, allows the calculation of the demagnetization coefficient n, quoted in reference 4 to be about 1.0 for thin plates oriented perpendicular to the applied field H. Following reference 5:

$$\vec{B} = \mu_0(\vec{H}_i + \vec{I}) = \eta\mu_0\vec{H}_i \qquad (15)$$

with:

$$H_i = H/(1-n(1-\eta)) \qquad (16)$$

where η is the non-superconducting fraction of the sample; and where the magnetization:

$$I = \rho\chi \qquad (18)$$

The minimum value of n, calculated by assuming that η = 0, is 0.875. The experimental value is well approximated by the one which is calculated for an oblate spheroid for which the length of the axis of revolution is the sample thickness and the length of the other axes is the diameter of the vanadium disc. Equation (2.20) of reference 6, yields for our sample n = 0.93.

In superconducting vanadium flux penetration is expected for an applied field

$H \geq (1-n)H_c$.

With our value n = 0.875 and the critical field H_c = 80 mT at 3 K (ref.7) in our sample flux penetration is not expected for applied fields H ≤ 10 mT, the field range used in the present work. No field penetration means that η = 0, as assumed for the calculation of n.

ACKNOWLEDGEMENTS

We would like to thank Prof. Y. Bruynseraede (K.U.L.) for the vanadium foil and Ir. J. Van Audenhove, CBNM, for punching the sample.

REFERENCES

1 L. Binard, A. Van den Bosch and J. Vansummeren, Thermochimica Acta, 51 (1981) 85.
2 A. Van den Bosch and J. Vansummeren, Thermochimica Acta, 82 (1984) 51.
3 F. De Schutter, Y. Bruynseraede and A. Gilbaert, IEEE Trans. Magn. Mag-19 (1983) 926.
4 R.P. Huebener, Magnetic flux structures in superconductors (Springer-Verlag Berlin) 1979.
5 A.C. Rose-Innes and E.H. Rhoderick, Introduction to superconductivity (Pergamon Press, Oxford) 1969.
6 H. Zijlstra, Experimental methods in magnetism, vol. 2 (North-Holland Publ.Co., Amsterdam) 1967.
7 D. Schoenberg, Superconductivity (Cambridge University Press) 1965.