Deformation thermomagnetic effect in tin

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The effect consists of excitation of a magnetic moment in a single crystal of a nonmagnetic metal by a heat flow. Torsional deformation is required for the appearance of the magnetic moment. With tin as an example, it is shown that the excited moment is directly proportional to the heat flux and to the deformation of the sample. The anisotropy of the effect, which is very large in tin, is studied. The temperature dependence of the effect is determined.

We have previously observed [1] that heat flow produces a magnetic moment in single crystals of metals. The induced moment is changed by torsion deformation of the sample. It was clear that the appearance of the effect is due to inhomogeneous deformation of the crystal.

A. F. Andreev has called attention to the fact that in the presence of torsion deformation in the sample there can appear a circular current component due to the dependence of the kinetic coefficients of the metal on the strain. It is this current which induces the magnetic moment. In a homogeneous medium, obviously, the effect does not occur. Andreev's idea was subsequently developed in calculations by Lebedev [2].

In this paper we present the results of further investigation of the deformation thermomagnetic effect in tin. We determine the dependence of the thermomagnetic effect on the heat flux, on the deformation of the sample, and on its temperature; we investigate the anisotropy of the effect.

MEASUREMENT PROCEDURE

The simplest instrument for the determination of the investigated effect is shown in Fig. 1. The sample is thermally insulated from the surrounding liquid helium by means of an inverted small Dewar. In our case, such a simple construction of the instrument is possible, since the thermal conductivity of the investigated samples (10—100 W/cm-deg) exceeds by many orders of magnitude the thermal conductivity of the gaseous helium. The heaters 3 and 4 are made of manganin wire wound on the sample. The wire is wrapped by several layers of paper. The heater 3 is used to produce heat flow along the sample, while heater 4 serves to check on the absence of parasitic effects due to the variation of the average temperature of the sample and of the instrument. The thermometer 5 monitors the sample temperature. The change of the magnetic field in the sample is determined with the aid of a superconducting SKIMP interferometer [3], the input loop which is made of superconductor 6 and lies outside the inverted Dewar. The solenoid 7 is used to calibrate the installation. The instrument is covered with a superconducting lead shield 8 and a magnetic permalloy shield.

During the course of the experiment, time plots are obtained of the readings of the SKIMP installation following several cycles of turning the heater current on and off. The direction of the current through the heaters is alternately reversed, so as to exclude the magnetic field of the heaters from the obtained data. A typical plot of one of the measurements is shown on the right side of Fig. 1. The plus and minus signs mark the turning on of the current of heater 3 in the two directions. It is seen

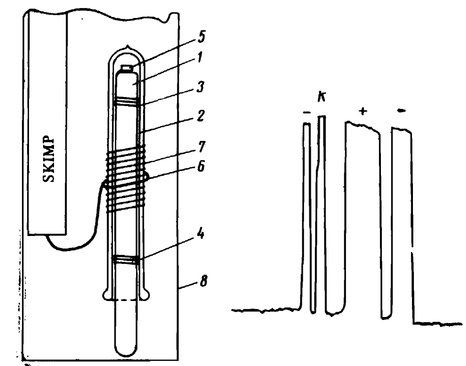

FIG. 1. Diagram of instrument for the observation of the thermomagnetic effects: 1—sample, 2—Dewar, 3, 4—heaters, 5—thermometer, 6—superconducting loop, 7—solenoid, 8—lead screen; right—typical time plot of the readings of the superconducting SKIMP interferometer.

from the plot that the heat flux excites a magnetic field in the sample. In this case, the field is approximately 10^{-5} Oe, which follows from a comparison of the signal with the spike when the current through solenoid 6 is turned on (callout K).

In the investigation of the influence of the strain on the effect, we used the instrument shown in Fig. 2. The torsion stress was transmitted to sample 1 through tubes 2 and 3 via clutches 4 and 5. The magnitude of the applied torque could be determined from the torsion of the spring 3′ and of the tube 3. The torsion of tube 2 was negligibly small. The torsion angle of the sample was measured optically by means of a system of mirrors 3, which were rigidly connected to the ends of the sample through tubes 7. The remaining part of the installation is similar to that described above.

The object of the investigation was tin, which is a typical nonmagnetic metal. During the course of the work we investigated a large number of single crystals grown mainly by two methods. At the start of the work, the samples were grown in lamp-black-coated glass molds by the Bridgman method. The mold was removed from the sample by etching. Subsequently, the single crystals were drawn in vacuum from the melt by the Czochralski method. In both cases, the samples were close in form to a cylinder of diameter ~5 mm and length ~8 cm. The crystallographic orientation of the samples was determined by x-ray diffraction. The resistivity of the samples at 4.2°K was $\sim 10^{-9}$ Ω-cm, thus indicating high purity of the initial metal.

MEASUREMENT RESULTS

1. The excited magnetic flux HS in the sample is determined by the heat flux Q in the sample. A change in the direction of Q leads to a change in the direction of

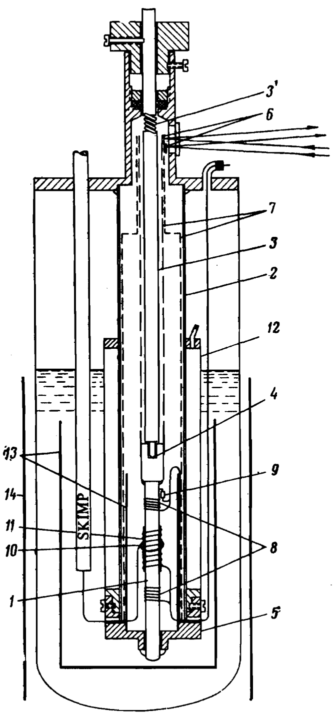

FIG. 2

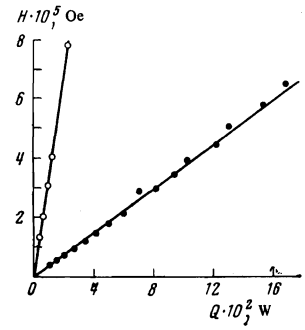

FIG. 3

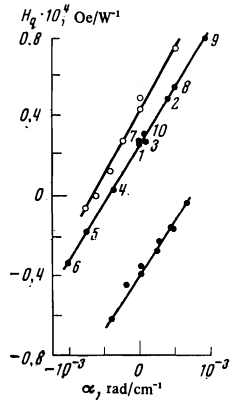

FIG. 4

FIG. 2. Installation for the investigation of the influence of twist deformation on the magnitude of the effects: 1—sample, 2, 3, 3′, 4, 5—mechanical system for transmitting the load to the sample, 6, 7—system for the measurement of the strain of the sample, 8—heaters on the sample, 9—thermometer, 10—superconducting loop of input transformer of the SKIMP installation, 11—coil for calibration, 12—Dewar thermal insulation of the sample, 13—lead shields, 14—permalloy shields.

FIG. 3. Magnetic field excited in samples by different heat fluxes Q.

FIG. 4. Dependence of the thermomagnetic effect on the torsion strain for three tin samples grown along the [100] axis. The numbers of the points indicate the sequence of the measurements.

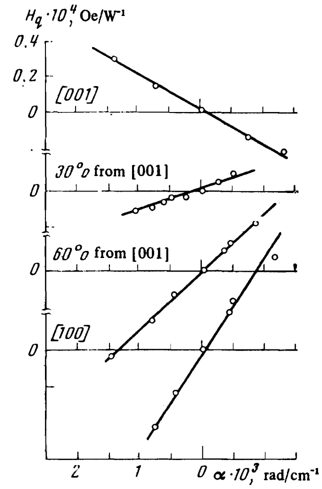

FIG. 5

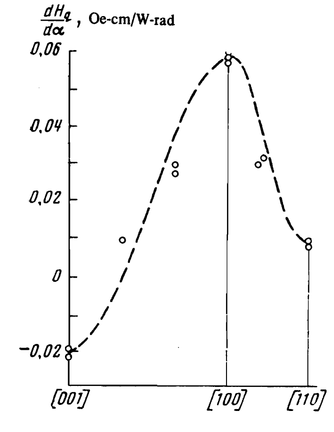

FIG. 6

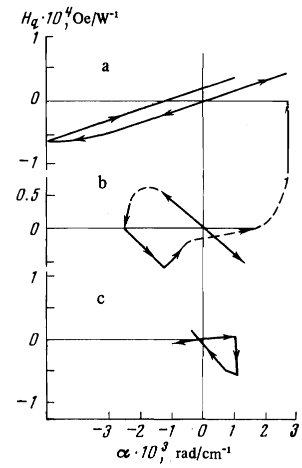

FIG. 7

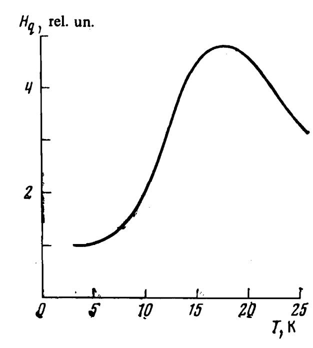

FIG. 8

FIG. 5. Dependence of the thermomagnetic effect on the torsion strain for several samples grown in the {100} plane.

FIG. 6. Anisotropy of the deformation thermal magnetic effect in the planes {100} and {001}. Circles—experimental results, dashed—simplest character of anisotropy.

FIG. 7. Thermal magnetic effect at large twist strains: a—sample grown along {110}, b—along {001}, c—at angle 30° to [001] in the {100} plane.

FIG. 8. Change of the strain-induced thermomagnetic effect with temperature.

the field. The magnetic field is directly proportional to the heat flux to the sample—see Fig. 3. Consequently, the magnetic moment excited by the heat flux can be described by the relation $H/q \equiv H_q$, where H is the excited field and q is the heat-flux density. We assume H_q to be positive if the magnetic field is directed towards a higher temperature.

2. The torsion torque applied to the sample changes the value of H_q. At small stresses and strains, H_q changes in direct proportion to the sample strain. The change of H_q with the strain is fully reversible (Fig. 4). In perfect samples, the value of $dH_q/d\alpha$ does not depend on the initial value of H_q (the sample torsion angle α is positive if the torsion of the warm end of the sample is clockwise). We henceforth assume on all curves that $H_q = 0$ at $\alpha = 0$.

3. As seen from Fig. 5, which shows plots of H_q against the torsion angle α for samples grown in the {100} plane, the value of $dH_q/d\alpha$ changes together with the crystallographic orientation of the sample. An appreciable anisotropy is observed even in the highest symmetry plane {001} of tin—see Fig. 6.

4. The foregoing results on the influence of the strain were obtained for samples grown by the Czochralski method, which seem to be the most perfect in their structure. Only in this case did we obtain values of $dH_q/d\alpha$ that were sufficiently well reproducible to determine the anisotropy of the effect.

During the first stage of the work we attempted to obtain anisotropy data by using samples grown in glass molds. However, reproducible values of $dH_q/d\alpha$ could be obtained only for samples grown along directions near [110]. The value of $dH_q/d\alpha$ for samples in the remaining directions varied from sample to sample in random fashion, although after prolonged annealing ($T \sim 180$–$200°C$, $t \sim 12$ hours) it did approach gradually the value obtained subsequently for "perfect" samples. Only in 10 out of 30 investigated samples was the initial value of $dH_q/d\alpha$ close to that typical of "perfect" tin crystals. The quantity $H_q(\alpha = 0)$ depended on the conditions under which the sample was prepared. Thus, whereas for "perfect" samples we had $H_q(\alpha = 0) \approx 3 \times 10^{-5}$ Oe/W, in most samples grown in glass molds we had $H_q(\alpha = 0) \approx (0.3-1.2) \times 10^{-3}$ Oe/W. We attributed the value of $H_q(\alpha = 0)$ to the stresses that can arise in single crystals during their growth. Annealing of the sample decreases somewhat the value of $H_q(\alpha = 0)$. This procedure, however, calls for a number of precautions, since it is easy to introduce additional stresses into the crystals near the melting temperature, owing to their high plasticity.

We note that for certain "oblique" directions we were unable to obtain reproducible values of $dH_q/d\alpha$ even in samples grown by the Czochralski method. Thus, for samples grown near the direction (65°, 30°) we obtained in succession $dH_q/d\alpha = -0.037$, -0.11, and -0.035 Oe-cm/W-rad.

5. A reversible linear change of H_q with sample strain occurs only in the region of small strains, $\alpha \lesssim 10^{-3}$ rad/cm. If we produce a large strain in the sample, then the character of the change of $H_q(\alpha)$ becomes more complicated and irreversible, accompanied by the appearance of various types of hysteresis loops (Fig. 7). In individual directions, we observed with increasing deformation a steep almost jumplike change of H_q, which increased in absolute value by more than dozens of times.

6. The results reported above pertain to 4.2°K. None of the relations change up to the superconducting transition point of tin. In the superconducting phase, the values of H_q and accordingly of $dH_q/d\alpha$ decrease by approximately two orders of magnitude. Although in all samples investigated in the superconducting phase we have observed a change of H_q with deformation of the sample, the magnitude of the effect was at the borderline of the possible experimental errors.

Measurements performed in a larger temperature interval (with the aid of the instrument of Fig. 1) have shown that H_q increases monotonically with increasing temperature above 5°K, reaching a maximum at ≈ 18°K—see Fig. 8. A similar character of the change of H_q was observed for all the investigated samples, but the maximum increase of H_q could exceed that shown in Fig. 8.

An investigation of samples with large initial value of $H_q(\alpha = 0)$ has shown that the character and magnitude of variation of H_q as the sample goes over into the superconducting phase depend on the state of its surface. A sharp decrease of H_q is observed for samples with mirror-finish surface. It is obvious that the question of the character of the variation of H_q in the superconducting phase calls for further research.

DISCUSSION OF RESULTS

The aggregate of the results offers unequivocal evidence that heat flow can excite in a metal a magnetic moment whose value is determined by the deformation of the sample.

The possible appearance of strain-induced thermomagnetism is the result of the following simple consideration. Heat transport in metals is described by the following system of equations:

$$j=\sigma E+\beta\nabla T,\quad q=\gamma E+\rho\nabla T.$$

It follows here from the Onsager principle that $\gamma = -\beta T$.

In the absence of a total net current through the sample, $j \equiv 0$, the thermal electric field is $E = -(\beta/\sigma)\nabla T$. When the sample is deformed, the kinetic coefficients change, in first approximation linearly in the strain u (see, e.g., [4]). Accordingly in this case, for example, $\sigma = \sigma_0 + \sigma' u$ (σ' is the derivative of the coefficient with respect to the strain). If the sample is subjected to a torsion strain $r\alpha$, then it obviously acquires a circular current component

$$j_\alpha=\beta\left(\frac{\sigma'}{\sigma}-\frac{\beta'}{\beta}\right)r\alpha\nabla T,$$

even though the total current through each section of the sample perpendicular to ∇T is indeed equal to zero.

The onset of a circular component can be visualized by assuming that in a sample with a temperature gradient there exist simultaneously two current components. One of these components is connected with the heat flux and the other with the thermoelectric field. The two components are equal, and in a homogeneous sample they are exactly opposite. In a sample with torsion deformation, the currents move opposite each other along helices, but the thicknesses of these helices are in general different. As a result, a net circulating current is produced. The electric field, being potential, cannot cancel out this current component.

The magnetic field excited by the heat flux is directly proportional to the ratio of the torsion strain of the sample to the thermal electric current, $j_T = \alpha\sigma q/K$, where α, K and σ are expectedly the coefficients of the differential thermal emf, the thermal conductivity, and the electric conductivity of the material. When the ratio $\alpha\sigma/K$ changes, H_q will also change. The experimentally obtained $H_q(T)$ dependence (Fig. 8) indeed agrees with the temperature dependence of $\alpha\sigma/K$ in tin.

It is obviously possible to establish a unique connection between the thermomagnetism of the sample and its strain only if the internal stresses in the sample are initially small. In the general case, in the presence of a complicated stress field in the sample, the net thermomagnetic moment is determined by the distribution of the circular current, which are altered by the deformation of the sample. This case does not lend it-itself to a simple analysis. The complex stress field appears, of course, in a cylindrical sample also when it goes over from elastic to plastic deformation. We encounter these effects on the H_q curves at large deformations of the sample (see Sec. 5). The various hysteresis phenomena, in our opinion, are also due to the redistribution of the strain and the sample. In general, all the experimental data show that thermal magnetization effect is extremely sensitive to the state of the sample, to the distribution of the stress field, etc. One cannot exclude the possibility that by using this effect we can obtain information that is useful for elasticity theory. For example, the different character of $H_q(\alpha)$ (Fig. 7) may be due to the anisotropy of the dislocation-formation energy [5].

In the present paper we have confined ourselves to an analysis of thermomagnetism in the region of small elastic strains. As seen from Fig. 7, the anisotropy of thermomagnetism is large and is observed even in those directions where other kinetic coefficients are isotropic (the $\{001\}$ plane). It is probable that data on the anisotropy of the effect can yield information on the differential characteristics of the spectrum of the electrons of the metal. For this purpose, however, a more detailed theoretical analysis of the entire effect is necessary. The phenomenological analysis presently performed [2] of the possible anisotropy of the effect has shown that the experimentally observed anisotropy can indeed take place in the $\{001\}$ plane. Quantitative estimates of the possible magnitude of the effect for an isotropic metal have led to a value $dH_q/d\alpha \sim 0.1$ Oe-cm/W-rad, which is close to the values obtained in experiment.

CONCLUSION

We present in this article the results of an investigation of the deformation thermomagnetic effect in tin, but it was shown earlier [1] that this effect is present also in other metals. Deformation thermomagnetization of metals was an unexpected effect. It seemed that a heat flux could not excite a magnetic field in a metal, inasmuch as in high-symmetry single crystals there is no linear connection between a polar vector (heat flux) and an axial vector (magnetic field). Until a complete theory is developed, it is difficult to determine the limits within which the thermomagnetic effect can be useful in the investigation of the electronic characteristics of a metal, but it is obvious even now that it yields important additional information on the perfection of prepared single crystals of metals and on their mechanical characteristics. The magnetic field due to thermomagnetism is small, but this source field must be taken into account in all the cryogenic devices based on working in a zero field.

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[1] N. V. Zavaritskiĭ, ZhETF Pis. Red. **16**, 99 (1972) [JETP Lett. **16**, 67 (1972)].
[2] V. V. Lebedev, Zh. Eksp. Teor. Fiz. **67**, 1161 (1974) [this issue, p. 577].
[3] N. V. Zavaritskiĭ and A. N. Vetchinkin, Prib. Tekh. Éksp. No. 1, 247 (1974), VINITI 7576.
[4] S. C. Hunter and R. F. N. Nabarro, Pros. Roy. Soc. **220**, 542, 1952.
[5] N. S. Brar and W. R. Tyson, Canad. J. of Phys. **50**, 2257, 1972.

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