The de Haas-van Alphen effect and damping of helicons during plastic deformation in aluminum

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The behavior of the amplitude of the de Haas–van Alphen effect and of helicon wave damping during deformation of aluminum by uniaxial tension at a temperature of 1.3 °K is studied. The elongation of the sample was measured simultaneously. On transition to the plastic deformation region, the Dingle temperature and helicon wave damping are found to increase. The dependence of these two quantities on the tensile stress and their recovery after annealing at 150 and 500 °C are studied. The investigation shows that the technique based on measurement of the Dingle temperature and helicon wave damping in a single experiment permits one to make a separate study of point defects and dislocations produced during plastic deformation.

This paper reports results obtained from an experimental investigation of how defects originating during plastic deformation simultaneously influence helicon damping and the de Haas-van Alphen (DHVA) effect in aluminum. Plastic deformation was induced by a uniaxial tensile stress applied during the course of the measurements at 1.3 K.

The (oriented) samples, which were $0.8 \times 4 \times 40$-mm monocrystalline strips of aluminum having the resistivity ratio $\rho(293^\circ)/\rho(4.2^\circ) = 19\,000$, were grown from a melt contained in a demountable graphite mold, using the technique of[1]. The produced single crystals were annealed 3 hours at 500°C. An electron-microscopic study of one sample revealed no stacking faults or grain boundaries. The density of dislocations in this sample was 10^8 cm^{-2}.

The deformation of the samples was achieved in a creep regime. Tensile stresses up to 3 kgf/mm^2 were applied in steps of about 0.06 kgf/mm^2. When the load had been fixed at each step the stationary elongation and electronic properties of the samples were measured.

Our experiments investigated essentially the resonance parameters of standing helical waves at $\lambda/2 = d$, where λ is the wavelength and d is the thickness of the sample. Helicon damping was determined from the Q of the resonance, and the DHVA amplitude was determined from the amplitude of the resonant-frequency oscillations.[2,3] All measurements were obtained in a magnetic field, at strengths up to 16 kG, directed along the [110] axis of the samples and perpendicular to the direction of the tensile stress. With this orientation we observed oscillations of γ orbits in the third zone of the Fermi surface of aluminum. The helicon frequencies were of the order of 10^2 Hz and satisfied the conditions of a local limit.

From the measured Q of the helicon resonance the transverse magnetoresistivity ρ was calculated by means of the relation[1)]

$$Q = {}^1\!/\!_2[1 + (RB\cos\theta/\rho)^2]^{1/2},$$

where, besides Q, R is the Hall constant (1.02×10^{-12} ohm-cm/gauss[5]), B is the magnetic field, and θ is the angle between the field and a normal to the surface of the sample.

The Dingle temperature before deformation was determined from the field dependence of the oscillation amplitude in a wide range of magnetic fields (from 10 to 17 kG). During the deformation process the oscillations were registered only around 13.5 kG. By comparing the field oscillations for the deformed and undeformed samples in an identical magnetic field we determined the increment of the Dingle temperature for the deformed samples. The deformation of a sample was determined from the shift of the upper end of the rod (protruding from the cap of the cryostat) that was used to apply a tensile stress to the sample. Substituting a steel sample for the aluminum, we measured in advance, and subtracted, the shift associated with the deformation of the rod itself and of other parts of the tensile loading apparatus.

The dependence of all the experimentally measured quantities on the tensile stress applied to the two samples is shown in Figs. 1 and 2. The dependence of ϵ on σ is seen to be linear on both sides of a break at $\sigma_0 = 0.4$ kgf/mm^2. We consider this break to indicate the onset of plastic deformation. This hypothesis is supported by the fact that for $\sigma < \sigma_0$ the resistivity (ρ) and Dingle temperature (T*) remain constant within experimental error limits and begin to increase after the break (ρ begins to increase at a point ~0.1 kgf/mm^2 to the right of σ_0).

The deformed samples were annealed in two stages: 7 hours at 140°C followed by 3 hours at 500°C. Following each stage the samples were again placed in the apparatus for measuring helicon damping and the oscilla-

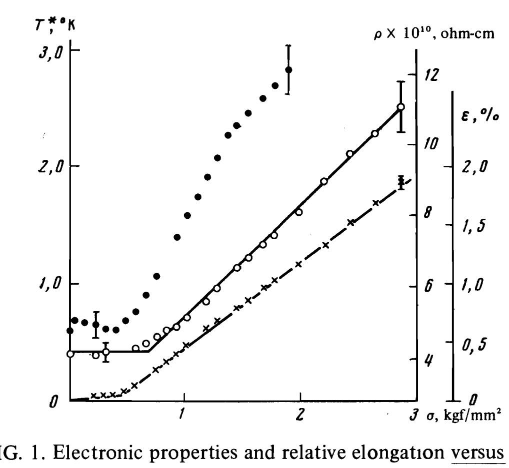

FIG. 1. Electronic properties and relative elongation versus tensile stress for sample Al-1 ([111] axis along the sample, [011] axis along the normal, magnetic field along [$\bar{1}$10]). ●—Dingle temperature T*, O—magnetoresistivity, X—relative elongation $\epsilon = \Delta l/l$.

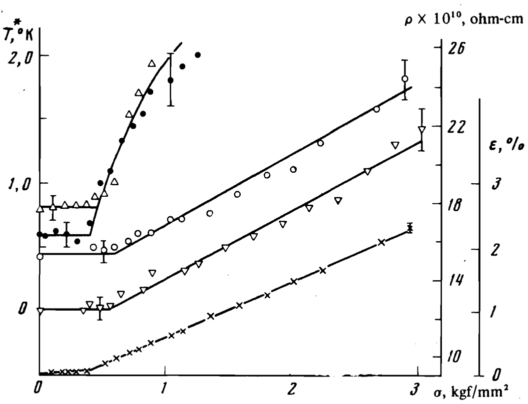

FIG. 2. Electronic properties and relative elongation versus tensile stress for sample Al-2 ([001] axis along the sample, [100] axis along the normal, magnetic field along [110]). ●—Dingle temperature T* during the first deformation, ∇—magnetoresistivity ρ during the first deformation, Δ—Dingle temperature T* during deformation after annealing at 500°C, O—magnetoresistivity after annealing at 500°C. The curve of relative elongation (X) during the first and second deformations was reproduced with ~10% accuracy.

Sample	Measured quantity	Before deformation	After deformation	After 140°C anneal	After 500°C anneal
Al-1	T^*, °K	0.6 ± 0.1	Above 2.8	3.0 ± 0.3	0.8 ± 0.1
	ρ, ohm-cm	$(4.1\pm0.3)\cdot10^{-10}$	$(11.2\pm0.6)\cdot10^{-10}$	$(5.3\pm0.3)\cdot10^{-10}$	$(4.2\pm0.3)\cdot10^{-10}$
Al-2	T^*, °K	0.6 ± 0.1	Above 2.0	Above 2.0	0.8 ± 0.1
	ρ, ohm-cm	$(12.3\pm0.9)\cdot10^{-10}$	$(21.9\pm1.8)\cdot10^{-10}$	$(14.0\pm1.0)\cdot10^{-10}$	$(15.1\pm1.1)\cdot10^{-10}$

tion amplitude; the results are given in the table. One sample was subjected to the deformation process a second time following the 500°C anneal (Fig. 2). Figure 3 demonstrates that the measured properties of the sample were restored qualitatively after the annealing process. The first anneal (at 140°C) practically restores the Q of helicon resonance, while leaving the DHVA amplitude at the noise level. For both samples the first anneal removes ~85% of the increment $\Delta\rho$ resulting from plastic deformation. The 500°C anneal has almost no effect on the Q of helicon resonance, which in some cases is even slightly reduced (see the table). At the same time the DHVA amplitude is restored to almost its value before deformation. The 500°C anneal removes 85—90% of the Dingle temperature increment resulting from plastic deformation.

The foregoing data show that the recovery of the plastically deformed samples during the anneals passed through at least two stages. On the basis of information given in the literature about the annealing of vacancies[6] and dislocations[7] in aluminum it is assumed that the first stage (below 140°C) anneals out mainly point defects generated by the plastic deformation, while the second, high-temperature, stage (above 350°C) anneals out dislocations. Let us compare, for example, the states of sample Al-1 before deformation and after deformation followed by the 140°C anneal (states a and c in Fig. 3). In accordance with the foregoing hypothesis, these states differ in that the density of dislocations is greater in the second state. Figure 3 and the table show that the transverse magnetoresistivity remained almost identical but that the Dingle temperature changed by a factor of almost five. It is interesting that in state c the effective relaxation time computed

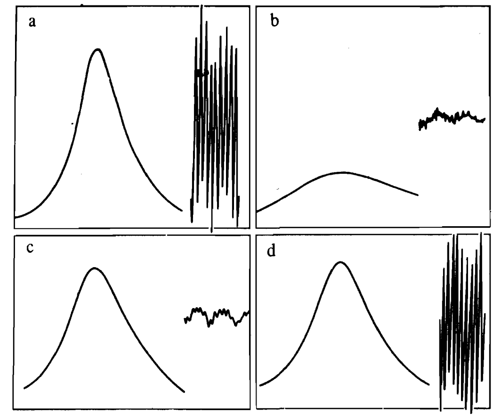

FIG. 3. Experimental traces of helicon resonance and DHVA oscillations in sample Al-1 for the different stages: a—before deformation, b—after 2% deformation, c—after annealing at 140°C, d—after annealing at 500°C. Resonance was observed in the field B ≈ 7 kG; the fragments of oscillation traces correspond to B ≈ 13.5 kG.

from ρ is 300 times greater than the time derived from the Dingle temperature.

It follows from our data (Fig. 3 and the table) that the damping of helicons, i.e., the magnetoresistivity, is sensitive to point defects, while the DHVA amplitude is sensitive to dislocations. This conclusion is consistent with the hypothesis advanced in[8] that the DHVA amplitude is much more sensitive than electrical resistance to dislocations. Our results therefore show that it is possible to study separately the point defects and dislocations generated by plastic deformation, using a technique whereby the amplitude of the DHVA effect and the damping of helicons are measured simultaneously.

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1)More exactly, a linear combination of the idagonal components of the magnetoresistivity tensor. [4]

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