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THE DEFORMATION SCATTERING MECHANISM AND CONDUCTION ELECTRON DISTRIBUTION FUNCTION IN ALUMINIUM*

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The influence of low-temperature plastic deformation on the electrical resistivity and magnetoresistance of aluminium is studied experimentally. During deformation realized by multiple slip, anisotropy of the electronic distribut ion function is independent of dislocation density, but the magnetoresistance has a maximum, associated with effective electron scattering at small angles in long-range stress fields. Conduct ion electron scattering at point deformation defects essentially makes the distribution function isotropic, as seen in growth of the temperature-dependent addition to resistivity and in decline of the relative transverse magnetoresistance in the temperature range 4·2–30 K.

As we know, the distribution function (DF) of conduction electrons in metals in an electrical field is very different from that of a free electron gas, because of the shape of the Fermi surface (FS) of real metals and anisotropy of electron scattering [1]. The electronic relaxation mechanisms due to crystal lattice defects are very complicated because of the peculiarities created by the stress fields. Short-range stresses which result in isotropic scattering can be created both by impurity atoms and by dislocation pileups in intersecting slip planes, as well as by dislocation cores. Long-range stresses might arise from separate dislocations as well as clusters of impurity atoms. The peculiarity of the dislocation scattering mechanism is evidenced in the fact that the deviation from Matthiessen's rule due to the presence of the two (temperature and defect) mechanisms diminishes with increase in the dislocation contribution to electrical resistivity [2, 3] but the DF tends to that of an ideal crystal [4].

The presence of defects has an influence on anisotropy of the contribution of different regions of the FS to the DF and is manifest in the electrical resistivity of the metal. In [1] it has been shown theoretically that allowance for anisotropy of scattering by phonons in the case of a perfect crystal lattice

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changes the electrical resistivity ρ by several times even with a spherical FS. Allowance for impurity scattering is displayed in the form of a deviation from Matthiessen's rule [5, 6].

The influence of electron scattering by point defects on the DF of aluminium has been studied in [7, 8] and the temperature dependence $\rho_D(T)$ due to the presence of dislocations has been determined experimentally in [9].

There is an experimental investigation of the temperature dependence of ρ and of the transverse magnetoresistance (TMR) $\Delta\rho_H/\rho$ of polycrystalline Al with different static lattice defects (impurities, dislocations, secondary quenching defects) in [10]. In the presence of extended defects, a correlation is observed between the temperature dependence of $\Delta\rho_H/\rho$ and the value $\Delta\rho/\rho_{res}\cdot\rho_{id}$, where ρ_{id} is the measured resistivity value of the most perfect specimen; $\Delta\rho$ — value characterizing deviation from Matthiessen's rule; and ρ_{res} — residual resistivity; $\Delta\rho=\rho-\rho_{res}-\rho_{id}$. There are maxima on the temperature curves of $\Delta\rho_H/\rho$ and $\Delta\rho/\rho_{res}\cdot\rho_{id}$ near 20 K, the introduction of extended defects raising the value of $\Delta\rho_H/\rho$ and reducing $\Delta\rho/\rho_{res}\cdot\rho_{id}$ relative to a specimen with a preponderance of impurity scattering.

A detailed investigation of the influence of electron-dislocation scattering on transfer phenomena in aluminium is needed in order to determine the importance of long-range stress fields. So far the principal mechanism of plastic deformation of Al has been established, the role of defect interaction during the different stages of deformation has been determined and experience on identification of the density of introduced defects as a function of the initial state of a specimen has been accumulated. The problem can therefore be solved with the help of low-temperature plastic deformation by studying the dependences of magnetoresistance of deformed specimens on temperature, magnetic field and deformation.

We used poly- and single crystal specimens of aluminium. The polycrystalline specimens (Al-1 and Al-2) were subjected to staged low-temperature deformation in compression and tension respectively, followed by annealing at room temperature. The single crystals (Al-3, Al-4, Al-5, Al-6, Al-7, Al-8) with [100] oriented along the tensile axis were deformed once with different degrees of deformation. All the specimens were machined with the electroarc method and had the same size. Low-temperature deformation was performed with the help of universal equipment comprising a loading element which was in a hot zone and removable load chambers which provided for deformation in compression and extension at helium temperatures. The degree of compression was estimated on the basis of identical strain hardening curves for uniaxial compression and extension [11]. The degree of extension was verified with the help of a micrometer indicator which registered the change in length of specimens with accuracy 0·01 mm. The electrical resistivity was measured with a potentiometer at temperatures from 4·2 to 30 K, registered with an (Au+Fe)–Cu thermocouple. The initial state of specimens, that is, their frequency and perfection, was verified using the resistivities at room and helium temperatures. The dislocation density was estimated from the increment of residual resistivity [12].

EXPERIMENTAL RESULTS AND DISCUSSION

Specimen Al-1 has dependence of residual restisivity ρ_0 on degree of deformation shown in Fig. 1. Curve *1* corresponds to the dependence of relative increment $\Delta\rho_0/\rho_0^{in}$ on deformation ε, measured immediately after mechanical compression (state 1) where $\Delta\rho_0/\rho_0^{in}=(\rho_0-\rho_0^{in})/\rho_0^{in}$; ρ_0^{in} — residual resistivity in initial state ($\varepsilon=0\%$, $T=4{\cdot}2$ K); ρ_0 — resistivity of deformed specimen at $T=4{\cdot}2$ K; $\rho_{273}^{in}/\rho_0^{in}=8000$. The $\Delta\rho/\rho_0^{in}$ values on curve *2* were obtained after deformation and 24-hour annealing at room temperature (state 2). It is known that regions of point defects — vacancies or interstitial atoms — are formed during deformation. Those defects are annihilated during annealing at room temperature, and that results in reduction of residual resistivity. The weak minimum for state 2 at $\varepsilon \simeq 2$–3% might be associated with the appearance of Cottrell atmospheres during deformation.

Figure 2 shows the temperature-dependent part $\rho_T = \rho - \rho_0$ of the specimen Al-1 as a function of ε. For state 1 ρ_T grows with ε. The observed dependence of ρ_T for state 2 differs from the results of [2, 3]. This is probably due to the higher purity of the specimen used here. It seems that anisotropy of the DF in the given deformation range (state 2) is independent of dislocation density in a zero magnetic field.

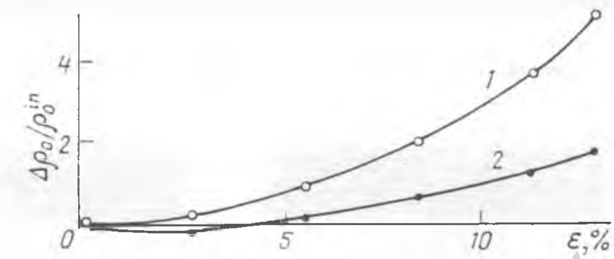

FIG. 1. Deformation dependence of relative increment of resistivity of specimen Al-1 after deformation (curve *1*) and annealing (curve *2*).

Figure 3 shows the temperature dependences of relative TMR $\Delta\rho_H/\rho$ of Al-1 in states 1 and 2, where $\Delta\rho_H/\rho = (\rho_H - \rho)\rho$ and ρ_H – resistivity in a magnetic field at a certain temperature. A general feature of all the curves for state 1 is that $\Delta\rho_H/\rho$ is lower than for the initial state ($\varepsilon = 0$). The characteristic maximum ($T = 20$ K) falls with rise of ε, that is, the defects introduced in the case of state 1 make the DF isotropic. The temperature dependences $\Delta\rho_H/\rho$ for state 2 are more complicated. There are

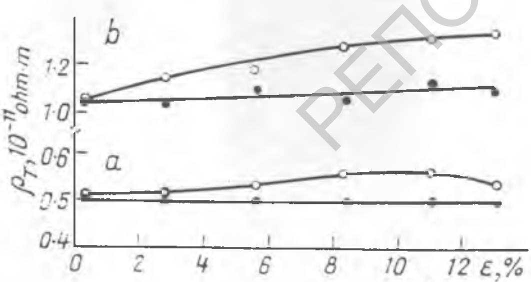

FIG. 2

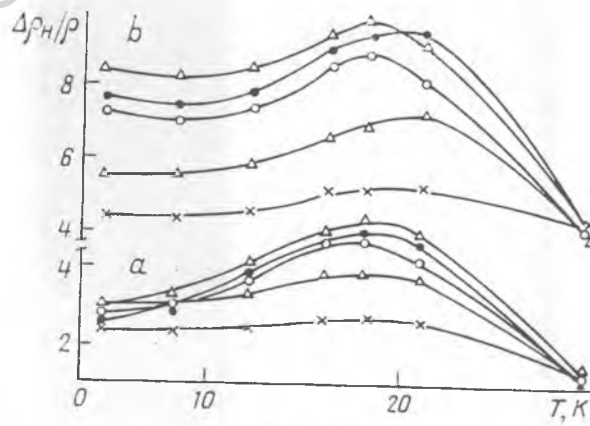

FIG. 3

FIG. 2. Temperature-dependent part of deformation resistivity of specimen Al-1 as function of deformation at $T = 16$ K (*a*) and $T = 21$ K (*b*), ○, ● – states 1 and 2 respectively.

FIG. 3. Temperature dependences of resistivity of specimen Al-1 in magnetic field at different deformations: *a* – transverse field $H = 1{\cdot}1 \times 10^6$ A/m; *b* – $5{\cdot}6 \times 10^6$ A/m; ● – $\varepsilon = 0$; ○, △ – $\varepsilon = 3\%$; ×, ▲ – $\varepsilon = 11\%$ in states 1 and 2 respectively.

$\Delta\rho_H/\rho$ values both larger and smaller than those in the initial state. In weak magnetic fields the temperature curve of $\Delta\rho_H/\rho$ intersects the curve of the initial state at $T = 8$ K and passes below it at higher temperatures. This is a characteristic feature for large deformations; the increment of $\Delta\rho_H/\rho$ at $T = 18$ K relative to $T = 4{\cdot}2$ K falls with rise of ε. In stronger magnetic fields the relative TMR is higher than the initial value only for small ε; this is true up to $\simeq 20$ K. But the rate of growth of $\Delta\rho_H/\rho$ with T is less than for the initial state and the relative size of the maximum is roughly the same for different ε.

The deformation curves of relative TMR shown in Fig. 4 exhibit an interesting feature. In weak magnetic fields the TMR is almost independent of deformation at $T=4{\cdot}2$ K and at $T=30$ K. In strong magnetic fields the TMR on the deformation curve in the small deformation range ($\varepsilon \simeq 3\%$) at helium temperature has a maximum which is also observed at $T=18$ K and disappears at 30 K.

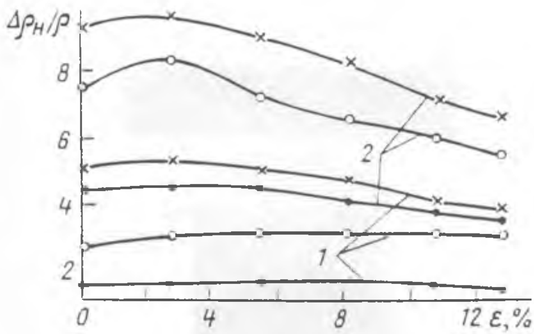

FIG. 4

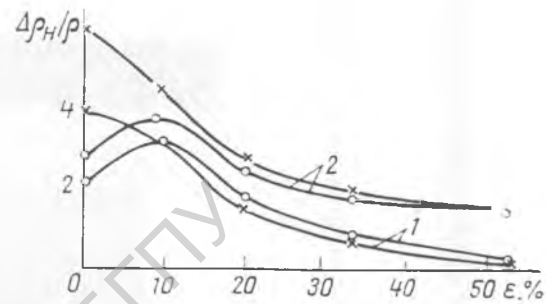

FIG. 5

FIG. 4. Dependence of magnetoresistance of Al-1 on deformation in state 2: *1* — in transverse field $H=1{\cdot}1\times10^6$ A/m; *2* — $5{\cdot}6\times10^6$ A/m; ○ — at $T=4{\cdot}2$ K; × — $T=18$ K; ● — $T=30$ K.

FIG. 5. Dependence of magnetoresistance of Al-2 on deformation in state 2: *1* — in transverse field $H=1{\cdot}1\times10^6$ A/m; *2* — $5{\cdot}6\times10^6$ A/m; ○ — at $T=4{\cdot}2$ K; × — 18 K.

The principal deformation mechanism in these experiments is dislocation sliding in multiple planes. The shape of the $\Delta\rho_H/\rho$ curves in weak and in strong fields at 4·2 K shows that the contribution to anisotropy of the DF by the magnetic field is varied. A dislocation network produces a rise in the scale of anisotropy of the DF similar to low-temperature anisotropic scattering by long-wave phonons

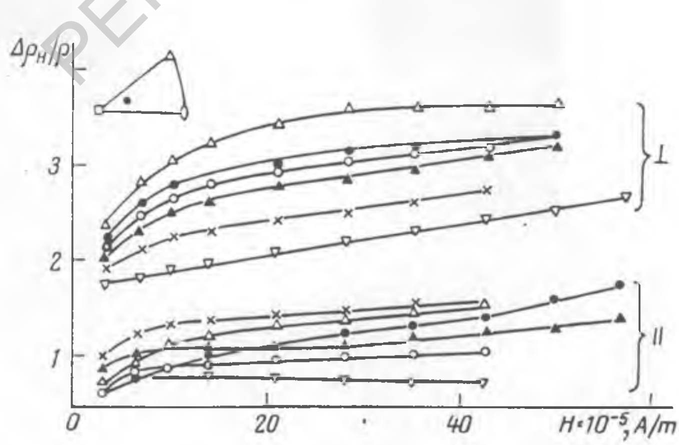

FIG. 6. Magnetoresistance of single crystal specimens Al-3 (● — $\varepsilon=0\%$), Al-4 (▲ — 6%), Al-5 (○ — 9%), Al-6 (△ — 11%), Al-7 (× — 19%), Al-8 (▽ — 25%) at $T=4{\cdot}2$ K as function of strength of transverse (⊥) and longitudinal magnetic field (||). In inset "●" denotes orientation of specimens relative to principal crystallographic axes: □ — [100]; △ — [111]; 0 — [110].

[10, 13]. On that basis, we can conclude that small-angle scattering in long-range stress fields plays a substantial part, its effectiveness being higher in a magnetic field [14]. The different behaviour of $\Delta\rho_H/\rho$ in weak fields could be due to the low topological anisotropy of the DF, and the constant TMR with rise of ε could be explained by the combined effect of small-angle scattering and magnetic breakdown [15]. This fact does not permit isolation of the DF anisotropy due only to scattering anisotropy in its pure form. The identical growth of $\Delta\rho_H/\rho$ in strong magnetic fields at 4·2 K provides evidence that electron scattering by long-wave phonons makes a more effective contribution to anisotropy of the DF apart from the dependence on dislocation density. On the other hand, the deformation dependence of $\Delta\rho_H/\rho$ at $T=18$ K, where the addition of a small-angle scattering mechanism at dislocations does not increase anisotropy of the DF, is typical. The qualitative features of the dependence of the TMR on ε for Al-2 (Fig. 5) during uniaxial tension are similar to those for Al-1. The only difference is that the maximum of the DF with that form of deformation is more pronounced in both strong and in weak fields. This could be attributed to the fact that sliding during uniaxial tension takes place in the smallest of mutually intersecting planes, resulting in a less complicated dislocation network. Small-angle scattering in long-range stress fields is more effective and occurs even in weak fields.

Figure 6 shows the field dependences of the transverse and longitudinal magnetoresistance $\Delta\rho_H^{\perp}/\rho$ and $\Delta\rho_H^{\parallel}/\rho$ at $T=4{\cdot}2$ K of all the investigated single crystals. The behaviour of the TMR of specimen Al-3 in initial state is typical for magnetic field orientation in which open magnetic-breakdown paths are lacking. The field dependence of specimens Al-4, Al-5 is very similar in shape, but the $\Delta\rho_H^{\perp}/\rho$ values are smaller than in Al-3. There is an appreciable growth on transition from smaller to greater deformations, and the field dependence of $\Delta\rho_H^{\perp}/\rho$ for Al-6 lies above those for the initial and deformed specimens. For large deformations (Al-7 and Al-8) the TMR is correspondingly smaller, the field dependence tending towards linear growth with deformation. In [14] it has been shown that, under conditions of small-angle scattering, the magnetoresistance emerges at an asymptotic value in large fields, higher than during isotropic scattering. Hence, the specimen Al-6 displays effective small-angle scattering of electrons at introduced dislocations.

Al-3 has a linear dependence in longitudinal magnetic field. This is due to the initial dislocation network, small-angle scattering by which results in a rise of magnetoresistance. The deformed specimens have field dependence closer to saturation. The $\Delta\rho_H^{\parallel}/\rho$ curves for specimens Al-6 and Al-7 lie above the curve for Al-3.

It is interesting to analyze the results from the standpoint of the theoretical work [1], in which the resistivity and its variation in a magnetic field are given in the form

$$\rho \sim P_{11}^{(0)} + cR_{11} - \frac{P_{12}^{(0)} + cR_{12}}{P_{22}^{(0)} + cR_{22}}; \qquad \Delta\rho_H \sim \frac{(P_{12}^{(0)} + cR_{12})^2}{P_{22}^{(0)} + cR_{22}},$$

where $p_{\lambda\lambda_1}^{(0)}$ and $cR_{\lambda\lambda_1}$ are the matrix elements of the collision operator determined by scattering at phonons and defects; c – defect (point and extended) concentration.

The growth of the temperature addition to the resistivity in state 1 with rise of degree of deformation can be represented as preferred growth of the diagonal matrix elements of the collision operator responsible for elastic scattering. Their growth precedes growth of the non-diagonal components in the expression for ρ_T which can be put in the form

$$\rho_T \sim P_{11}^{(0)} - \frac{(P_{12}^{(0)} + cR_{12})^2}{P_{22}^{(0)} + cR_{22}} - \frac{cR_{12}^2}{R_{22}}.$$

With rise of dislocation density in state 2 in the given range of deformation the non-diagonal matrix elements which describe phonon scattering in regions of dynamic perturbation, as well as nonsphericity of the FS, are more effective and the last two terms vary weakly with rise of dislocation density.

The relative TMR has a maximum on the deformation curve at $T=4{\cdot}2$ K if it is assumed that $P^{(0)}_{\lambda\lambda_1} \ll \ll cR_{\lambda\lambda_1}$. Then the existing initial magnetoresistance $\Delta\rho_H/\rho=\eta_i/(1-\eta_i)$, where $\eta_i=R^2_{12}/R_{11}R_{22}$ and η_i passes through a maximum as a function of ε. At high temperatures, where $\Delta\rho_H/\rho$ is weakly dependent on ε in state 2 it can be assumed the that $P^{(0)}_{\lambda\lambda_1} \gg cR_{\lambda\lambda_1}$ and $\dfrac{\Delta\rho_H}{\rho}=\dfrac{P^{(0)}_H\eta^0}{P^{(0)}_{11T}1-\eta^0)+cR_{11}}$, where $\eta^0=P^{(0)^2}_{12}/ /P^{(0)}_{22}P^{(0)}_{11}$ corresponds to the "pure" limit. At intermediate temperature we can assume $P_{\lambda\lambda_1}\sim cR_{\lambda\lambda_1}$ and the weak dependence of $R_{\lambda\lambda_1}$ on dislocation density causes a rapid change in $\Delta\rho_H/\rho$ with small change in the dislocation density.

Thus small-angle electron scattering in long-range stress fields in the presence of a magnetic field has a substantial influence on the electronic distribution function, expressed in the non-linear dependence of the matrix elements of the collision operator on deformation defect concentration.

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