Influence of nickel paramagnetic impurity on the softening of lead during the superconducting transition

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It is shown that introduction of a nickel paramagnetic impurity in lead leads to a considerable decrease of the softening of the metal during the superconducting transition. This may be due to the strong influence of the paramagnetic atoms on the spectrum of the electronic excitations in the superconductor.

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An investigation of the softening effect and its quantitative characteristics, namely the jump of the deforming stress $\delta\sigma_{ns}$ and the jump of the creep deformation $\delta\epsilon_{ns}$, which occur when the metal goes from the normal to the superconducting state during the course of deformation, was carried out in pure superconductors and in alloys with nonmagnetic impurities.[1–5]

The existing theories of the effective softening were constructed under the assumption of the isotropic BCS model for the same class of superconductors and superconducting alloys.[6,7] It follows, for example, from the Natsik fluctuation model,[6] the main conclusions of which are in good agreement with many experimental data, that the magnitude of the softening $\delta\epsilon_{ns}$ is given by

$$\delta\epsilon_{ns} = \frac{kT^*}{\kappa V}\ln\left[\frac{1}{2}\left(1 + e^{\Delta(T)/kT}\right)\right]; \qquad T_0 < T < T_C, \tag{1}$$

where T_0 is the temperature that determines the conditions of the weak and strong damping of the dislocation segments, T^* is the effective crystal temperature and depends on the temperature T, κ is the crystal hardening coefficient, V is the activation volume, and $\Delta(T)$ is the energy gap of the superconductor. The dependence of the softening on the plastic properties of the metal manifest itself via κ and V. The logarithmic factor in this expression takes into account the change of the electronic spectrum during the superconducting transition, so that the softening effect depends on the energy gap $\Delta(T)$.

It is known that small concentrations of nonmagnetic impurities exert a weak influence on the energy spectrum of a superconductor,[8] but can alter strongly its plastic properties. Therefore all the experimental data obtained to date on alloys with nonmagnetic impurities have made it possible to trace their influence on the softening effect mainly as via the change of the factor $kT^*/\kappa V$, and left open the question of how the effect changes when impurities that alter significantly the energy spectrum of the crystal are introduced into the crystal. In the present study we have attempted to obtain an answer to this question by studying the softening of lead into which a paramagnetic nickel impurity was introduced. According to the published data,[9,10] even a negligible concentration of the paramagnetic impurity alters the spectrum of the electronic excitations in the superconductor significantly, a fact manifest in a decrease of its energy gap and of its critical temperature. One can therefore expect the introduction of the paramagnetic impurity into the lattice of lead to reveal new and hitherto unknown singularities of the softening effect. To explain these singularities, a comparison was made between the dependences of the jump $\delta\epsilon_{ns}$ on the total deformation ϵ of polycrystals of pure lead and of the alloys Pb + 0.4 at.% Sn and Pb + 0.4 at.% Ni. The nonmagnetic (Sn) and paramagnetic (Ni) impurities were present in the alloy in the same phase state, forming a solid solution with the lead. The jump $\delta\epsilon_{ns}$ was measured at 4.2 °K by a procedure described in[11]. The obtained plots are shown in Fig. 1. Attention is called to the fact that the nonmagnetic (curve 1) and paramagnetic (curve 3) impurities exert opposite effects on the behavior of the function $\delta\epsilon_{ns}(\epsilon)$ relative to pure lead (curve 2). Whereas $\delta\epsilon_{ns}$ is larger in the alloy of lead with tin by a factor 1.5–2 than in pure lead at all deformations, in the alloy with nickel it is approximately one tenth as

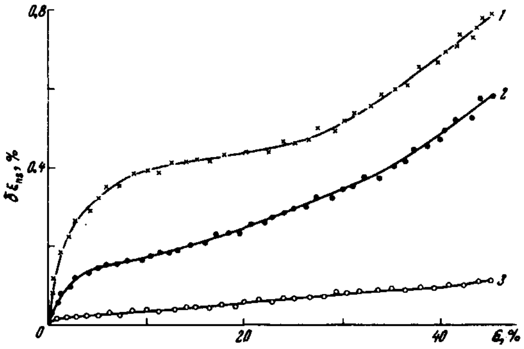

FIG. 1. Plots of $\delta\epsilon_{ns}(\epsilon)$ in polycrystals: in an alloy of lead with a nonmagnetic tin impurity (curve 1), in pure lead (curve 2), and in an alloy of lead with a paramagnetic nickel impurity (curve 3).

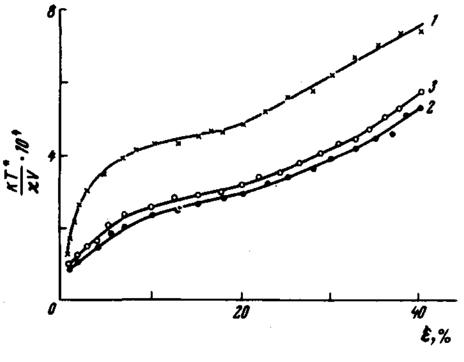

FIG. 2. Dependence of the factor $kT^*/\kappa V(\epsilon)$ in expression (1) for the same polycrystals as in Fig. 1.

large as in pure lead. To exclude the possible connection of such an inversion with different plastic properties whose influence on the investigated alloys is determined by the factor $kT^*/\kappa V$, independent experiments were used to measure the dependence of the hardening coefficient κ and of the activation volume on the deformation, and the results were used to plot the $kT^*/\kappa V(\epsilon)$ curves shown in Fig. 2.

A comparison of Figs. 1 and 2 shows unequivocally that the observed inversion of the softening effect in the alloy with nickel, and the large decrease of this effect, are not due to the influence of the nickel impurity on the plasticity of the alloy, for in accordance with Fig. 2 (curves 2 and 3) this influence leads not to a decrease but to a small increase of the factor $kT^*/\kappa V$ in comparison with pure lead. It remains therefore to conclude that the observed singularity of the softening effect in the alloy Pb + 0.4 at.% Ni is due to the strong decrease of the energy gap, owing to the appreciable influence of the paramagnetic nickel impurities on the energy spectrum of the electrons in the lead. The observed singularity, in our opinion, offers new proof that the softening of metals on going from the normal to the superconducting state is due to realignment of the electronic energy spectrum of the superconductor.

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[1] V. V. Pustovalov, V. I. Startsev, and V. S. Fomenko, Fiz. Tverd. Tela 11, 1382 (1969) [Sov. Phys.-Solid State 11, 1119 (1969)].

[2] G. Kostorz, Scr. Metall. 4, 95 (1970).

[3] V. P. Soldatov, V. I. Startsev, and T. I. Vaĭnblat, J. of Low Temp. Phys. 11, 321 (1973).

[4] G. Kostorz, J. of Low Temp. Phys. 10, 167 (1973).

[5] V. G. Bar'yakhtar, I. A. Gindin, I. S. Gubin, B. I. Druinskiĭ, V. P. Lebedev, Ya. D. Starodubov, and I. I. Fal'ko, Fiz. Tverd. Tela 15, 2947 (1973) [Sov. Phys.-Solid State 15, 1966 (1974)].

[6] V. D. Natsik, Zh. Eksp. Teor. Fiz. 61, 2540 (1971) [Sov. Phys.-JETP 34, 1359 (1972)]; Fiz. Nizk. Temp. 1, 465 (1975).

[7] M. I. Kaganov, V. Ya. Kravchenko, and V. D. Natsik, Usp. Fiz. Nauk 111, 655 (1973) [Sov. Phys.-Usp. 16, 878 (1974)].

[8] P. deGennes, Superconductivity of Metals and Alloys, Benjamin, 1965.

[9] A. A. Abrikosov and L. P. Gor'kov, Zh. Eksp. Teor. Fiz. 39, 1781 (1960) [Sov. Phys.-JETP 12, 1243 (1961)].

[10] E. Wassermann, Zs. Phys. 187, 369 (1965).

[11] V. P. Soldatov, V. I. Startsev, and T. I. Vaĭnblat, Phys. Stat. Sol. (a) 22, 109 (1974).