Activation conductivity of alloys with a negative temperature coefficient of resistance (TCR)

A. S. Shcherbakov, A. F. Prekul, and R. V. Pomortsev
Institute of Metal Physics, USSR Academy of Sciences

(Submitted 18 July 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **32**, No. 6, 425–429 (20 September 1980)

An increase of the TCR with decreasing temperature below ~80 K was observed in hardened alloys of transition metals that have a negative TCR. At $T \lesssim 80$ K the temperature dependence of the conductivity of alloys is well described by the Mott $T^{1/4}$ law.

PACS numbers: 72.15.Eb

The presence of a negative temperature coefficient of resistance (TCR) in alloys, whose original components are *d* metals, is now the subject of wide discussion (see Refs. 1 and 2 and the literature cited therein). The authors of this paper suggested[3] that a pseudogap is formed in the electron spectrum of nonequilibrium hardened alloys and that the properties of these alloys can be understood in terms of the Mott model.[4] This assumption was confirmed in a series of experimental papers (see Ref. 5 and the literature cited therein), where the magnetic, galvanomagnetic, and optical properties were studied in addition to the resistance in titanium-based alloys, which are typical representatives of the group of materials being examined.

We report in this paper that the electrical conductivity of alloys with a negative TCR often contains a term that has a temperature dependence of the form $\exp(-B/T^{1/4})$. Such a temperature dependence, known as Mott's law,[4] is characteristic of a jump conductivity with a variable jump length in disordered systems.

Until now, only the onset of negative TCR has been discussed in the literature; it has been pointed out that the $\rho(T)$ dependences are approximately linear. We performed a careful study of these dependences and noticed that very often they are nonmonotonic. For the analysis of the electrical conductivity, we chose seven alloys with a negative TCR with the following compositions: No. 1, Ti—9.8 at.% Mn; No. 2 and No. 3, Ti—9.8 at.% Cr; No. 4, Ti—4 at.% Fe; No. 5, Ti—5 at.% Fe; No. 6, Ti—6.5 at.% Fe; No. 7, Ti—8 at.% Fe quenched from 900 °C; and No. 8, Ti—8 at.% Fe quenched from 1000 °C. The numbering of the graphs in the figures corresponds to the numbering of the alloys.

Several $\rho(T)$ dependences are shown in Fig. 1. We shall discuss the sections of the $\rho(T)$ curves indicated by the arrows, where the TCR increases with decreasing temperature. (A sharp resistance drop in the helium temperature region is caused by the transition to superconducting state.) We focus attention on this feature because the existing theoretical models for alloys with a negative TCR (see Refs. 1 and 2 and the literature cited therein) predict monotonic $\rho(T)$ dependences with a saturation in the low temperature region.

Bearing in mind the results of earlier studies,[3,5] we assumed that the discussed

0021-3640/80/180401-04$00.60

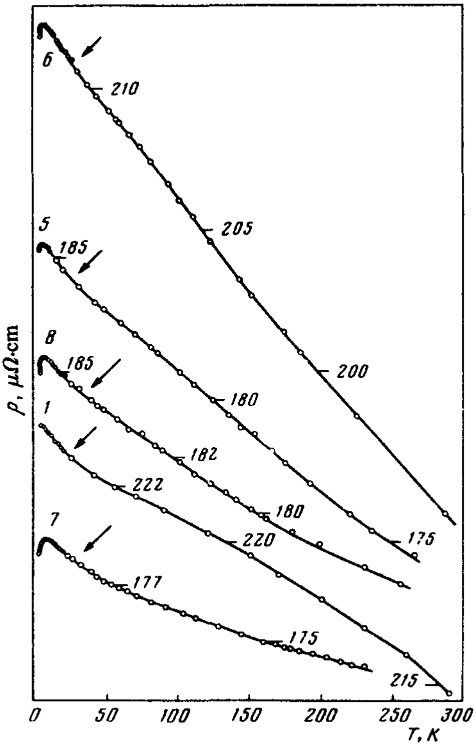

FIG. 1

effect may be due to an activation contribution to the conductivity of alloys. As is known, however, for activation mechanisms of conductivity $\sigma \to 0$ as $T \to 0$ K. We can see in Fig. 1 that it is hard to imagine an extrapolation of the $\rho(T)$ curves in which the resistance would increase without limit as $T \to 0$ K. Therefore, we chose the following expression as the interpolation formula for analyzing the $\rho(T)$ dependence at $T \lesssim 80$ K:

$$\sigma(T) = \sigma_0 + A\exp(-B/T^n), \tag{1}$$

where σ_0 is a temperature-independent contribution that takes into account the fact that the resistance remains finite as $T \to 0$ K.

To determine the value of n, we used the standard procedure of linearizing the experimental data in the log $\ln(\sigma - \sigma_0)$ versus log T coordinates, where σ_0 is the fitting parameter. After calculating the slope of the obtained lines, we found that $n = 0.250 \pm 0.003$ in all the cases. Thus, it was established that the temperature-dependent part of the alloy conductivity is described by the Mott law $\sigma \sim \exp(-B/T^{1/4})$.

Figure 2 shows the $\ln(\sigma - \sigma_0)$ vs $T^{-1/4}$ dependences. We can see that the $\sigma(T)$ of the alloys is very well described in a broad temperature range by the expression

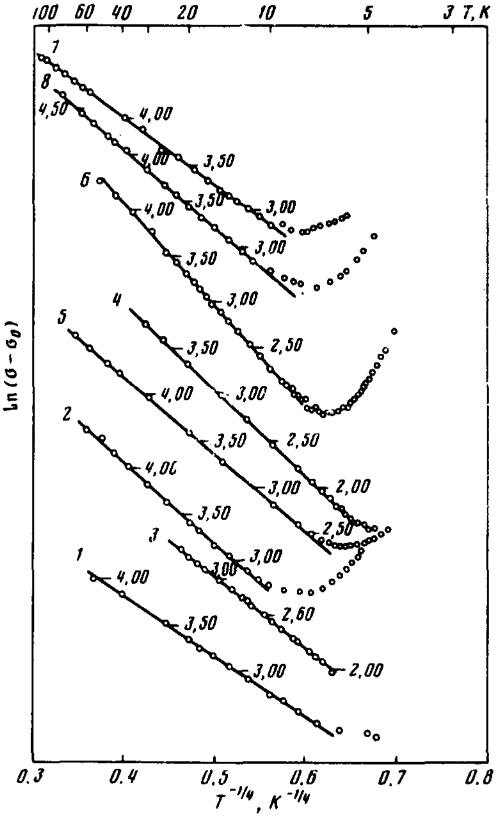

FIG.2

$$\sigma(T) = \sigma_0 + A\exp(-B/T^{1/4}). \tag{2}$$

To establish that this expression describes the $\sigma(T)$ behavior of the normal state of alloys in the entire low-temperature region, we investigated the $\sigma(T)$ dependence of the Ti—9.8 at.% Cr sample (graph 2 in Fig. 2) in a magnetic field $H = 130$ kOe, which was large enough for complete suppression of superconductivity in this sample (graph 3 in Fig. 2). A comparison of these data shows that suppression of the superconductivity established agreement between the experimental values of the conductivity and the dependence (2).

Thus, the introduction of the value σ_0 as an additive correction to Mott's law makes it possible to describe the low-temperature parts of the $\sigma(T)$ curves of alloys with a negative TCR. The relative deviation of the values calculated from Eq. (2) from those measured experimentally is $|(\sigma^{\text{calc}} - \sigma^{\text{meas}})/\sigma^{\text{meas}}| < 0.01\%$, i.e., it does not exceed the measurement error limits. Therefore, Eq. (2) gives almost ideal description of the extremal data in the interval $0 < T \lesssim 80$ K.

At the same time, the structure of Eq. (2) contradicts the existing concepts of transport effects in disordered systems. In fact, as Mott showed,[4] the localized and extended states cannot coexist at the same energy. Hence a metallic conductivity (σ_0) cannot coexist with an activation conductivity with a variable jump length, since both of these mechanisms are caused by the motion of electrons with energies close to the Fermi energy.

If such a good description of the experimental data by Eq. (2) is only an accident, then the parameters included in Eq. (2) are random numbers. However, our values of σ_0, which are of the same order of magnitude 4000–5000 $(\Omega\cdot\text{cm})^{-1}$, are close to the conductivity on the metallic side of the Anderson transition. In addition, the localization radii which can be estimated from the known values of "B" in Eq. (2) (we shall digress from the fact that we are dealing with a metallic-conductivity region), are equal to 5–10 Å, i.e., they are physically reasonable values.

Thus, both of the separately examined terms in Eq. (2) have a specific physical meaning and are reasonable quantitative characteristics from a physical point of view. On the other hand, they cannot be considered as additive contributions to the conductivity.

The main results of this report can be formulated as follows:

1) a Mott-type activation contribution was observed for the first time in the temperature dependence of the electrical conductivity of transition-metal alloys with a negative TCR; by taking this contribution into account, we were able to accurately describe these dependences.

2) The obtained interpolation expression for the $\sigma(T)$ dependence of alloys indicates that a metallic conductivity can coexist with an activation conductivity in this group of materials. This very unusual situation may stimulate a further development of the theory of transport effects in disordered systems.

The authors thank Professor I. M. Tsidil'kovskiĭ for many useful and stimulating discussions. The part of this work involving the use of a magnetic field was performed at the International Laboratory of Strong Magnetic Fields and Low Temperatures in Vrotslav, Polish People's Republic. The authors are grateful to N. E. Alekseevskiĭ, Assoc. Member of the USSR Academy of Sciences, and Dr. Ch. É. Bazan for making it possible to perform these investigations.

[1]Y. Imry, Phys. Rev. Lett. **44**, 469 (1980).
[2]M. Jonson and S. M. Girvin, Phys. Rev. Lett. **43**, 1447 (1979).
[3]A. S. Shcherbakov, A. F. Prekul, and N. V. Volkenshteĭn, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 703 (1977) [JETP Lett. **26**, 540 (1977)].
[4]N. F. Mott, Metal-Insulator Transitions (Russ. Transl., Nauka, Moscow, 1979).
[5]A. S. Shcherbakov, A. F. Prekul, and N. V. Volkenshteĭn, Fiz. Tverd. Tela **22**, 2301 (1980) [Sov. Phys. Solid State **22**,

Translated by Eugene R. Heath
Edited by S. J. Amoretty