THERMAL EMF AND THE THERMOMAGNETIC EFFECT IN COPPER-MANGANESE ALLOYS

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With the goal of studying the magnetic ordering at low temperature in metallic alloys which contain, in a nonmagnetic matrix, ions of transition metals with local magnetic moments, we earlier investigated the magnetic, electrical, and galvanomagnetic properties of copper-manganese alloys [1]. To obtain additional data on the magnetic ordering of the copper-manganese alloys we have investigated the thermal emf and the thermomagnetic effect.

We studied manganese-copper alloys with manganese content from 1.15 to 11.37 at.%. We used as initial materials for the alloys electrolytically refined copper with a copper content of 99.96% and manganese with a 99.95% manganese content. The thermal emf was measured by the potentiometer method using a photoelectrooptical amplifier (FEOU-18). The apparatus and the method of investigating the thermal emf is described in [2]. The magnetic field was created by a superconducting solenoid; measurements were made in fields of up to 40 kOe and temperatures from 4.2 to 55°K. Temperatures were controlled by copper-constantan and copper-gold + 25% cobalt thermocouples.

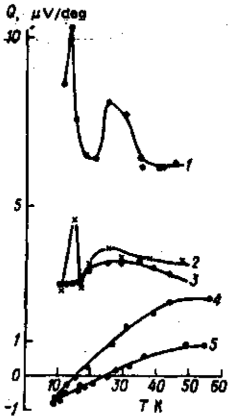

Fig. 1. Temperature dependence of the thermal emf Q(T) for alloys containing different concentrations of Mn with Cu: curve 1 is for 1.15; 2 for 2.3; 3 for 3.45, 4 for 5.7; 5 for 11.37 at.% Mn.

Thermal emf. Figure 1 shows the dependence of the thermal emf on the temperature. It is seen from the figure that the thermal emf decreases with increasing manganese concentration. A significant decrease in the thermal emf is observed for alloys containing 2.3 at.% manganese as compared with alloys containing 1.15 at.% manganese. For the alloys containing 1.15 and 2.3 at.% manganese, the maximum thermal emf is observed at temperatures of 13 to 15°K.

In the curves for the temperature dependence of the resistance in the same temperature interval the maximum resistance is observed. For alloys containing 1.15, 2.3, and 3.45 at.% manganese, a second maximum of the thermal emf is observed in the temperature interval from 20 to 25°K. In this temperature interval these alloys have resistance minima [3].

Such behavior of the temperature dependence of the thermal emf coincides with the theoretical data of N. Shula et al. [4]: the results of their calculation of the thermal emf showed the presence of a maximum at the Kondo temperature.

Knowing the value of the thermal emf for pure copper [5,6], we determined the sign of the impurity thermal emf. It turned out to be positive in the entire temperature interval of the measurements for samples with manganese concentration of 1 to 3%. For samples with manganese concentration of 5.7 and 11.37 at.% the impurity thermal emf is negative in the temperature interval from 10 to 18°K and 10 to 36°K, respectively, while at higher temperatures it is positive. The temperatures at which the sign of the impurity thermal emf changes (18 and 36°K) for alloys with manganese content of 5.7 and 11.37 at.% coincides with the temperatures of the ferromagnetic transitions in these alloys [1].

Because the amplitude of the scattering from the impurity potential of 3d metals in precious metals can be considered positive ($V > 0$) [7], the sign of the impurity thermal emf Q of the alloys is unambiguously determined by the sign of the S-d exchange interaction J (the impurity thermal emf $Q \sim JV$ [7-9]). According to out measurements, the impurity thermal emf is positive in the entire interval of measured temperatures (from 10 to 50°K); the S-d exchange interaction J between the conduction electrons and the electrons localized on an impurity atom consists of the sum of two interactions: a direct S-d exchange J_1 and an S-d mixing J_2

$$J(\mathbf{K}, \mathbf{K}') = J_1(\mathbf{K}, \mathbf{K}') + J_2(\mathbf{K}, \mathbf{K}'),$$

where K and K' are the wave vectors of the different electron states; $J_1 > 0$ always for $K = K'$. It is assumed that $J_2 < 0$ [10-13] and acts as a negative exchange interaction [14-15]. According to the results of the thermal emf measurement, $J > 0$ for alloys with manganese content of 1 to 3% in the temperature interval from 10 to 50°K. And because $J > 0$ when $|J_1| > |J_2|$, apparently in these alloys the direct S-d exchange interaction predominates.

Thermomagnetic effect. The thermomagnetic effect is the change of the thermal emf in a longitudinal magnetic field:

$$Q(H, T) - Q(0, T) = \Delta Q(H, T).$$

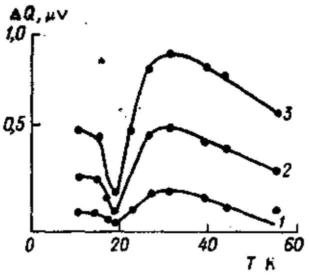

Fig. 2

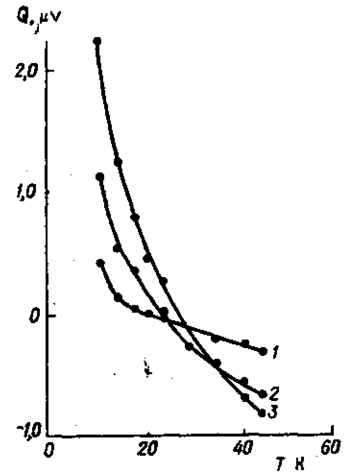

Fig. 3

Fig. 2. Temperature dependence of the thermomagnetic effect $\Delta Q(T)_H$ for a sample containing 5.7 at.% Mn in the magnetic fields H: curve 1 is for H = 12.9; 2 is for H = 25.7; 3 is for H = 38.5 kOe.

Fig. 3. Temperature dependence of the thermomagnetic effect $\Delta Q(T)_H$ for a sample containing 1.15 at.% Mn in the magnetic fields H: curve 1 is for H = 12.9; 2 is for 25.7; 3 is for 38.5 kOe.

For alloys containing from 2.3 to 11.37 at.% manganese, ΔQ is positive and grows with increasing magnetic field at all temperatures. In the curve of the temperature dependence of $\Delta Q(T)_H$ one observes maxima and minima (Fig. 2) in the same temperature interval in which the minima of the function $\Delta R/R(T)_H$ are observed, coinciding with the temperatures of the magnetic transition of CuMn alloys [1].

Samples containing less than 2.3 at.% magnanese have a characteristic temperature dependence $\Delta Q(TH)_H$ (see Fig. 3) which is sharply distinct from that of samples with manganese content of 2.3% and higher. The functions $\Delta R/R(T)_H$ and $\Delta Q(T)_H$ for a sample with Mn content 1.15 at.% have an analogous character: beginning at temperatures of 6-10°K up to 20°K, a sharp drop in $\Delta R/R(T)_H$ and $\Delta Q(T)_H$ is observed. Above a temperature of 20°K the decrease of $\Delta R/R(T)_H$ and $\Delta Q(T)_H$ with increasing temperature becomes smoother. The quantity $\Delta Q(T)_H$, moreover, changes sign. The temperature at which $\Delta Q(T)_H$ changes sign with increasing magnetic field. Above a temperature of 30°K, $\Delta Q(T)_H$ is negative for all values of the field.

It follows from [1] that alloys containing less than 2.3 at.% manganese do not have magnetic ordering. We noticed that alloys with manganese content above and below 2.3 at.% have functions $\Delta Q(T)_H$ of different character. This is evidently explained by the presence or absence of magnetic ordering in the alloys.

Thus, as a result of this investigation, it is established that the thermal emf falls with increasing manganese concentration. The maximum value of the thermal emf is of the order of 11 μV/deg for a sample with a manganese content of 1.15 at.% and the minimum is 1 μV/deg for a sample with a manganese content of 11.37 at.%. The thermal emf of a sample with manganese content 2.3 at.% is half as large as that of the sample with 1.15 at.% Mn. The theory of N . Shul and Vong is supported: the maximum thermal emf $Q_{max}(T)$ is observed at the same temperature $T = T_K$ where the minimum resistivity $\rho_{min}(T)$ is observed in the curve $\rho(T)$. (For samples with manganese contents of 2.3 and 3.45 at.% these temperatures were $T = T_K$ = 20 and 25°K, respectively.) It is shown that at temperatures coinciding with the temperatures of the magnetic transition temperatures, about 18°K for the 5.7 at.% Mn alloy and ~36°K for the 11.37 at.% alloy, a change in the sign of the impurity thermal emf $Q_i(T)$ is observed. The sign of the S-d exchange interaction J for samples containing 2.3 and 3.45 at.% manganese was determined. It was shown that the temperatures at which the anomaly in the temperature dependence of the thermomagnetic effect $\Delta Q(T)_H$ is observed coincide with the temperatures where the functions $\Delta R/R(T)_H$ and Ir(T) have maxima and minima. These temperatures correspond to the magnetic transition temperatures in these alloys.

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