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STUDY OF THE PHASE COMPOSITION OF METEORITIC IRON BY THE METHOD OF LOCAL X-RAY SPECTRAL ANALYSIS

(Presented by Academician I. P. Bardin, July 10, 1958)

Long-term investigations of iron meteorites have shown that their substance is a solid solution of iron, nickel (from 4 to 60%), and cobalt (from 0.3 to 0.7%), with inclusions of iron sulfide FeS and primary and secondary crystals of iron-nickel phosphide $(\mathrm{Fe, Ni})_3\mathrm{P}$. Iron meteorites containing approximately up to 6% Ni consist of a single α-phase; most meteorites contain more than 6% Ni and are a mixture of two phases, α and γ; and, finally, isolated meteorites containing about 60% Ni consist of a single γ-phase. Among the two-phase meteorites, the majority are so-called octahedrites, which have a coarse-crystalline Widmanstätten structure, while the smaller part, called ataxites, consists of a sufficiently homogeneous finely dispersed mixture of α- and γ-phases. In octahedrites the α-phase (the so-called kamacite) has the form of bands of various widths, arranged along the planes of the octahedron and bordered by thin strips of the γ-phase (the so-called taenite). Study of the composition of the individual phases of meteoritic iron plays an important role in the question of the origin of meteorites. These investigations make it possible to determine the degree of phase equilibrium and the diffusion phenomena characterizing the conditions of formation of iron meteorites.

Table 1

Element	α-phase	α-phase	γ-phase	γ-phase
	(1)	(4)	(1)	(4)
Ni, wt.%	52.6–6.81	3.3–5.8	13–48	31–54
Co, wt.%	0.25–0.83	0.43–0.61	0.02–2.1	0.04–0.15

A small number of works are known in which the chemical composition (1), lattice parameter (2), and microhardness (3) of the individual phases of iron meteorites were determined. The data of (1) refer to the average composition of the phases, but significant fluctuations of microhardness in the γ-phase in one and the same meteorite indicate the inhomogeneity of its composition. Recent investigations of the phase composition of several octahedrites (4) have shown

Fig. 2. Distribution of nickel, iron, and cobalt in the γ-phase

Figure 1: Fig. 2. Distribution of nickel, iron, and cobalt in the γ-phase

different results. Table 1 gives a brief summary of the results obtained in works (^{1},^{4}).

In work (^{4}) the γ-phase was separated by etching, and an attempt was made to determine the inhomogeneity of its composition across the band. But the results obtained, indicating a decrease in nickel content in the direction toward the boundary of the γ-phase, are questionable because of the imperfection of the method of phase separation. Meanwhile, precisely such data as the composition of the phases at the boundary between them and the character of the change in concentration of individual elements with distance from this boundary are of special importance for solving the question posed.

To the article by A. A. Yavnel', I. B. Borovskii, N. P. Il'in, and I. D. Marchukova, p. 256

a *b*

Fig. 1. Structure of different regions of the iron of the nickel meteorite Chebankol. *a* —region with broad bands and γ-phase, *b* —region of fine-grained plessite

To the article by E. N. Kondrat'eva, V. D. Fedorov, and K. P. Greshnykh, p. 365

Fig. 1. Shape of cells of *Chlorobium thiosulfatophilum.* 800×

As the method for studying the phase composition we chose X-ray spectral analysis of microvolumes, recently developed (^{5}). The object of study was the Chebankol iron meteorite (found in 1938), containing, according to analyses by M. I. Dyakonova, 9.03% Ni and 0.44% Co. It has a distinct Widmanstätten structure and belongs to the type of coarse-structured octahedrites (see Fig. 1). A study was made of the continuous distribution of iron, nickel, and cobalt, with the recording of concentration curves on passing across bars of the α-phase and bands of the γ-phase. The composition of the phases forming the Widmanstätten structure was determined, and in the case of a fine-dispersed mixture of phases the average composition was determined.

A typical result of the first series of measurements is presented in Fig. 2. Here, first of all, a sharp boundary between the phases is visible in the form of a jump in the content of all the principal components of the alloy. Further, in all measurements a rise in the nickel content and a decrease in the iron and cobalt contents are clearly seen from the center of the γ-phase band to its edge, with an extreme value at the very boundary of the phase.

Fig. 2. Distribution of nickel, iron, and cobalt in the γ-phase

The presence of a sharp boundary between the phases and the form of the con-

Fig. 3. Distribution of nickel, iron, and cobalt in the γ-phase with an inclusion of a finely dispersed mixture $\alpha + \gamma$

Figure 2: Fig. 3. Distribution of nickel, iron, and cobalt in the γ-phase with an inclusion of a finely dispersed mixture $\alpha + \gamma$

centration curves in the γ-phase show that, after crystallization, this meteorite was not subjected to heating that could have caused a change in the composition and ratio of phases in the temperature region below the transition $\gamma \to (\gamma + \alpha)$, or diffusion of nickel and cobalt at temperatures above this transition.

An important question is that of the equilibrium composition of the phases in iron meteorites. It is obvious that, at definite values of temperature and pressure, the equilibrium composition of the alloy will correspond to the composition of the phases at the boundary between them, even in the case where the entire system has not yet fully reached an equilibrium state.

As is seen from Fig. 2, both phases of meteoritic iron, despite its extremely slow cooling (as follows from the very coarse-crystalline structure of iron meteorites), are inhomogeneous in their composition, i.e., this system is not completely at equilibrium. The nickel content in the α-phase decreases from 7.6% in the main mass to 6.4% in a narrow layer at the very boundary with the γ-phase, while in the γ-phase the nickel concentration increases from 32% in the center of the band to 42% at its boundary. Therefore, the equilibrium nickel contents in this meteorite are 6.4% Ni for the α-phase and 42% Ni for the γ-phase. These values were repeated in different parts of the meteorite. The equilibrium cobalt content is 0.60% in the α-phase and 0.30% in the γ-phase, i.e., the concentration of cobalt in the γ-phase is lower than in the α-phase.

Comparison of the nickel data with the phase diagram of the Fe—Ni system, constructed under ordinary conditions (at normal pressure) (^{6}), showed that the results obtained correspond to temperatures differing among themselves by $\sim 20^\circ$. It is possible that such a discrepancy is to some extent

is explained either by the increased pressure during crystallization of the meteorite, or by a displacement of the surfaces of the phase diagram of the ternary system for an alloy containing about 0.5% Co.

On the other hand, the data on the character of the change in nickel concentration may indicate a decrease in the limit of solubility of nickel in the α-phase with cooling, beginning from some value of temperature, i.e., the line of transition $\alpha \to \alpha + \gamma$ in the region of low temperatures must have a bend toward lower nickel concentrations. Such a bend was noted earlier in the phase diagram of the Fe—Ni system (^{7}) and was also obtained from thermodynamic considerations (^{8}).

Fig. 3. Distribution of nickel, iron, and cobalt in the γ-phase with an inclusion of a finely dispersed mixture $\alpha + \gamma$

Measurements of the phase composition in regions of plessite where the bands of the γ-phase are separated by narrow bands of the α-phase showed an analogous picture of the distribution of elements. Within individual bands of the γ-phase, regions of a fine-grained mixture of $\gamma + \alpha$ phases were also observed. The distribution of nickel, iron, and cobalt in such a band is presented in Fig. 3. As can be seen, the nickel content in such fine-grained plessite is constant and amounts to 20%. The higher concentration of nickel compared with its average content in the meteorite may indicate that such a structure formed during a later transformation of the γ-phase (at lower temperatures). This result is also consistent with the type of structure, which indicates an initial stage of phase separation. The data obtained confirm the view of some investigators on the late formation of plessite of this type and give a certain idea of the kinetics of transformation in iron–nickel alloys.

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