concentration of the combusting component in the gas; a, thermal diffusivity; λ, thermal conductivity; R, universal gas constant; E, activation energy; q, thermal effect of the reaction per unit mass of the combusting component; k_0, preexponent; ρ_g, gas density. Subscripts: r, combustion; s, particle surface; d, delay; 0, initial conditions; g, gas; 1, 2) reaction regions.

LITERATURE CITED

1. V. S. Kravchenko and V. A. Bondar (eds.), Explosive Safety of Electrical Discharge and Friction Sparks [in Russian], Nedra, Moscow (1976).
2. A. G. Merzhanov, B. I. Khaikin, and G. K. Shkadinskii, "Establishing a steady flame distribution during ignition of a gas with a heated surface," Zh. Prikl. Mekh. Tekh. Fiz., No. 5, 42-48 (1969).
3. Ya. B. Zel'dovich, "A theory of ignition," Dokl. Akad. Nauk SSSR, 150, No. 2, 283-285 (1963).
4. E. S. Shchetnikov, Physics of Gas Comubstion [in Russian], Nauka, Moscow (1965).
5. V. N. Viklyunov and L. B. Sidonskii, "A theory of ignition of condensed systems by a hot surface," Dokl. Akad. Nauk SSSR, 152, No. 1, 131-133 (1963).

STABILITY OF THE MAGNETIC PROPERTIES OF IRON–COBALT ALLOY AT DIFFERENT ANNEALING TEMPERATURES

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The article presents the results of experimental investigations of the effect of the annealing temperature on the stability of the magnetic properties of the Fe–Co–2Mn alloy.

When highly homogeneous magnetic fields are required, magnetic materials are used which have high saturation induction and whose magnetic properties in operation are very stable. Among these materials are the iron–cobalt alloys type Permendur which at present are widely used in various fields of instrument making. The alloys Fe–Co–2V, Fe–Co–2Mn with additives V and Mn are used for making magnetic lenses of electron microscopes, pole shoes for NMR high-resolution radiospectrometers, and other instruments in radio electronics and computer technology. A number of authors [1-15] investigated these alloys to study the effect of the conditions of plastic deformation, of thermomagnetic and other kinds of treatment on their magnetic properties and on the homogeneity of the structure. The source of inhomogeneity of the magnetic field, which limits the resolution of the instruments, is the course crystal structure of the material [5, 8]. A fine-grained structure of iron–cobalt alloys is attained by adding some alloying elements to them [8]. The structure can also be improved [3, 4, 12] by choosing the optimal regime of heat treatment. Investigations [3, 4, 14, 15] showed that it is possible to attain an axial texture when certain deformation procedures are applied, and that textured pole shoes in NMR radio spectrometers can be used.

The above-mentioned authors showed that by using various kinds of treatment it is possible to improve the magnetic properties of iron–cobalt alloys. Further improvement of the resolution of instruments is not only attained by reducing the inhomogeneity of the field but also as a result of increasing the stability of the magnetic properties in time [6].

In connection with the widespread practical application of these alloys the study of the stability of their magnetic properties in time with different kinds of mechanical, thermal, thermomagnetic treatment is of practical and scientific interest. The articles [9, 10] report on investigations of the stability of the magnetic properties of specimens of Fe–Co–2V alloy for the range of annealing temperatures encompassing all the characteristic regions of the phase diagram [2, 7]. The data of [9] show that when the annealing temperature

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is raised, the internal stresses, dislocation density and other microdefects in the specimens of the alloy are reduced, at the same time the irreversible processes connected with aging, diffusion and other phenomena are accelerated, and the time of stabilization of the magnetic properties is reduced.

The investigations [10] established that when specimens of Fe—Co—2V during heat treatment are exposed to a magnetic field, the time of stabilization of their magnetic properties is on an average 30% shorter than when the same annealing temperatures are applied but without a magnetic field.

It was shown in [3, 4] that iron—cobalt alloys with equal amounts of cobalt and iron, when alloyed with 2% Mn, have maximal saturation induction and high magnetic permeability.

The present work includes experimental investigations of the stability of the magnetic properties of iron—cobalt alloy with an alloying addition of 2% Mn with different annealing temperatures. The test specimens of Fe—Co—2Mn alloy (Fe 49%, Co 49%, Mn 2%) had the shape of an ellipsoid of revolution with the ratio of the semiaxis equal to 10. The choice of such a shape ensures that in the process of the investigation the magnetization of the specimens is homogeneous throughout their bulk. Annealing of the specimens was carried out in vacuum so that there was practically no oxidation of their surface. In the investigation the selected annealing temperatures of 600, 750, 820, 980, 1100°C encompassed all the characteristic regions of the phase diagram of the system of the alloy Fe—Co [2, 7]. When the alloy attains 730°C, the α-phase in it is transformed from the ordered state (α') to the disordered state (α), and at 980°C the magnetic transformation with transition of α-phase to γ-phase sets in.

When investigating the stability of the magnetic properties of electrotechnical steel during aging, Druzhinin et al. [16] pointed out that these processes are not only affected by machining and heat treatment but also by the heating and cooling rate. With this rate increasing, the losses in coldrolled transformer steel during aging increase, too.

In our experiments the heating rate was V_h = 200°C/h, and the cooling rate was V_{cl} = 100°C/h. The holding time at the specified annealing temperature was one hour. Such a regime of heat treatment was applied to all the tested specimens and with all the investigated annealing temperatures. After annealing the stable state of the structure of the specimens is not attained at once but only after some time. The transition from the metastable thermodynamic state to a more balanced state causes a temporary change of the magnetic properties of the specimen. These changes were continuously recorded with the aid of a special magnetometric installation, the same as in [9-11].

The experimental results in the form of the curves J = f(t), characterizing the change of magnetization of the specimens of alloy Fe—Co—2Mn vs time for different annealing temperatures, are presented in Fig. 1.

It follows from an examination of the graphs that at the initial stage of the process the change of magnetization of the specimens proceeds more intensely, and after a certain time its practical stabilization sets in. For the mentioned annealing temperatures of 600, 820, 1100°C the times of stabilization of magnetization are respectively equal to: t^{st}_{600} = 130, t^{st}_{820} = 85, t^{st}_{1100} = 45 h. Analogous curves J = f(t) were obtained for the annealing temperatures of 750, 980°C with stabilization times t^{st}_{750} = 105 and t^{st}_{980} = 60 h. Experimental observations showed that after the mentioned times of stabilization, the magnetic properties remain practically unchanged for a long time (more than 700 h).

The experimental results for intermediate annealing temperatures are described by analogous curves, and they differ only in the time of stabilization. The general shape of these curves, like in [11], can be described by the equation

$$J = J_0 e^{-\lambda t} + J_\infty (1 - e^{-\lambda t}),$$

where J_∞ is the steady-state value of the magnetization of the specimen after the transition of its crystal structure from the metastable to a more balanced state.

From an analysis of the experimental data there follows a common regularity for all the tested specimens: the higher the annealing temperature, the shorter the time of stabilization of their magnetic properties.

Temporary changes of the magnetic properties of ferromagnets may be due to a change of their domain or crystal structure. Instability due to the rearrangement of the domain

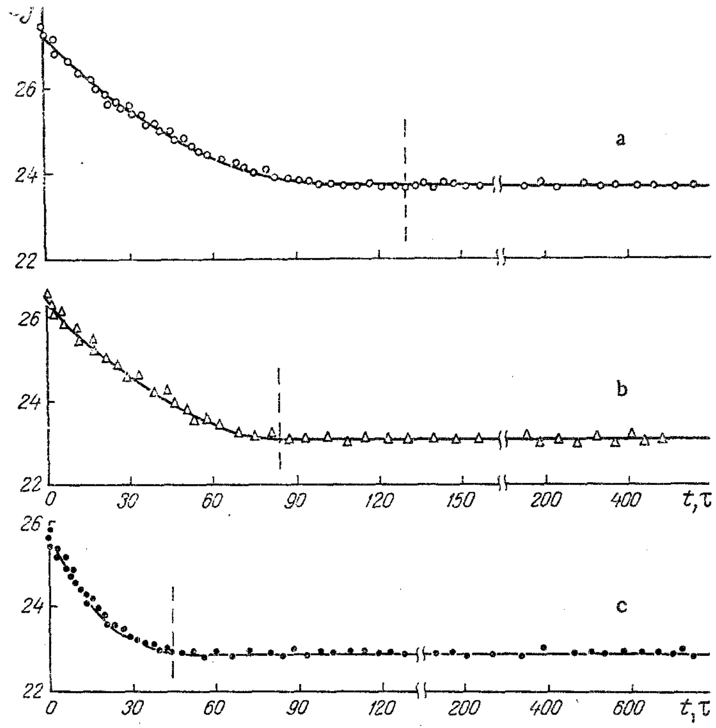

Fig. 1. Curves of the change of magnetization of specimens of alloy Fe—Co—2Mn vs time for the annealing temperatures T = 600 (a), 820 (b), and 1100°C (c).

structure is of a reversible nature whereas when it is due to the transition of the crystal structure from the metastable thermodynamic state to a more balanced state, it is irreversible. Stabilization of the crystal structure may be accompanied by a change of the density of dislocations and microdefects, of the degree of dispersity of phases and of their redistribution. The investigations [12, 13] of iron—cobalt alloy showed that annealing at 400-600°C entails the redistribution of the alloying additions at the places where there are dislocations and other microdefects, and this leads to the formation of clusters. This is accompanied by a decrease of the lattice parameter of the alloy and a change of the concentration of the alloying element in the flawless region.

Annealing at 600°C, which corresponds to the region of ordered α'-phase reduces internal stresses, the density of dislocations and other microdefects, and it ensures thereby some level of stabilization of the crystal structure. However, full stabilization sets in only after a certain time, and it can be seen from Fig. 1a that the time of stabilization of the magnetic properties of the specimens amounts to 130 h. During this time there occur irreversible processes in the crystal structure, probably in connection with the formation and equilibrium redistribution of clusters accompanied by aging and elastic aftereffect in individual microvolumes.

When the annealing temperature is higher, then in the regions of disordered α-phase and of the transient $\alpha \rightleftarrows \gamma$-phase as well as in the γ-phase there occurs a more intense decrease of internal stresses, of the density of dislocations and of other microdefects, and this in turn manifests itself in the time of stabilization of the magnetic properties of the tested specimens. It follows from Fig. 1b, c that the time of stabilization becomes shorter, and for the annealing temperatures 820, 1100°C it amounts to 84, 45 h, respectively. Raising the annealing temperature accelerates artificial aging and causes the crystal structure of ferromagnetic specimens to change from the metastable to a more balanced state.

The results obtained in the investigation of the stability of the magnetic properties of the alloy Fe—Co—2Mn are not only of theoretical interest from the point of view of studying phenomena of magnetic relaxation in ferromagnets, they are also of practical interest in connection with the widespread use of these alloys in various fields of instrument making.

NOTATION

t, time; T, temperature; J, magnetization; λ, parameter depending on the annealing temperature and the properties of the ferromagnet; v, heating and cooling rate; α, α', γ, designation of phases in the phase diagram.

LITERATURE CITED

1. I. F. Libsch, E. Both, G. Beckman, D. Warren, and R. I. Franklin, "Iron—cobalt and iron—cobalt—nickel alloys," J. Met., Trans. ASME, 188, No. 2, 287-296 (1950).
2. C. W. Chen, "Alliages cobalt-fer magnetiquement doux," Cobalt, 22, No. 3, 2-21 (1964).
3. Investigation of the Effect of the Structure of Magnetic Materials on the Homogeneity of the Magnetic Field with the Object of Devising Precision (with Inhomogeneity up to 10^{-10}) NMR Magnets with High Resolution: Report B370 860 [in Russian], Minsk (1974).
4. In: Elaboration of the Theory of the Effect of the Structure on the Physical Properties of Metals for the Purpose of Predicting Failure and Obtaining Materials with Specified Properties: Report R760 24 592, Minsk (1980), pp. 181-317.
5. K. Cuno and Ch. Simidzu, "Investigation of the homogeneity of materials of pole shoes of electromagnets," J. Jpn. Inst. Met., Nikhon Kindzoku Gakkaisi, 39, 570-578 (1975).
6. A. Lechet, Nuclear Induction [Russian translation], IL, Moscow (1963).
7. R. Bosort, Ferromagnetism [Russian translation], IL, Moscow (1956).
8. Patent No. 389 1475 (USA).
9. P. P. Galenko, "Investigation of the stability of the magnetic properties of the alloy Fe—Co," Vestsi AN BSSR, Ser. Fiz.-Tekh. Navuk, No. 1, 83-85 (1982).
10. P. P. Galenko, "Investigation of the effect of thermomagnetic treatment on the stability of the magnetic properties of the alloy Fe—Co," Inzh.-Fiz. Zh., 42, No. 6, 966-971 (1982).
11. P. P. Galenko, "Investigation of the effect of the annealing temperature and of the holding time on the stability of the magnetic properties of the alloy Fe—Co," Inzh.-Fiz. Zh., 45, No. 6, 987-992 (1983).
12. A. G. Kozlov and A. K. Shukevich, "The effect of the temperature on the structure of the alloy Fe—Co—2V," Vestsi AN BSSR, Ser. Fiz.-Tekh. Navuk, No. 2, 27-30 (1981).
13. D. M. Dzhavadov, A. A. Alekseev, Yu. D. Tyapkin, and R. B. Levi, "Investigation of the effect of chromium and vanadium on the structure of ordered alloys iron—cobalt by the method of electron microscopy and NGR," in: 5th All-Union Conference on Ordering of Atoms and the Effect of Ordering on the Properties of Alloys, Tomsk Univ. (1976), pp. 123-127.
14. A. I. Arbuzov, A. G. Kozlov, N. V. Kremen'kova, and A. K. Shukevich, "Creation and possibilities of using textured pole shoes," in: New Physical Methods and Means of Inspecting Industrial Products [in Russian], Nauka i Tekhnika, Minsk (1978), pp. 274-278.
15. A. I. Arbuzov and S. A. Novikov, "Investigation of the magnetic microinhomogeneity of the alloy Fe—Co—2V," in: New Physical Methods and Means of Inspecting Industrial Products [in Russian], Nauka i Tekhnika, Minsk (1978), pp. 279-282.
16. V. V. Druzhinin, L. K. Kurennykh, and A. A. Kozhurov, "Increase of losses in electrotechnical steel during its aging," Vestn. Elektropromyshlennosti, No. 8, 37-42 (1975).