MAGNETIC RELAXATION OF Fe WITH VARIOUS CONCENTRATIONS OF Si IMPURITY ATOMS

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We give the experimental results of an investigation of the effect of silicon impurity atoms on magnetic relaxation in iron.

When the magnetizing field, the temperature, the mechanical forces, and the other factors acting on a ferromagnetic are varied, its magnetic state is established not instantaneously but, as a practical matter, over a finite period of time which ranges from 10^{-9} sec to tens of minutes, hours, and even days. In ferromagnetics which have a domain structure, the temporary effects are particularly marked in materials with high permeability in the region of weak fields, when the magnetization varies as a result of a process of displacement of the boundaries between the domains. The potential causes of magnetic-relaxation processes in them may be the following phenomena: diffusion of impurity atoms, interaction between spin waves (magnons), and also their interaction with phonons, with dislocations, and with other crystal defects.

As has been shown in a number of studies [1-17, etc.], depending on the structural changes, the magnetization conditions, the temperature, and other factors, we may distinguish several types of temporary effects in ferromagnetics. The investigation of these phenomena is both of practical importance, because they must be taken into consideration in determining the magnetic characteristics of the materials [15], and of theoretical importance in that they help to discover the deeper physical nature of magnetization processes.

The temporary effects in the magnetization and demagnetization of a ferromagnetic are due to the delay in the magnetization caused by the variation of the magnetic field H. In the establishment of thermodynamic magnetic equilibrium when the domain boundaries are displaced, an important role is played by the elastic aftereffect of the stresses (which is due to the phenomenon of magnetostriction), by the diffusion of impurity atoms, and by other microdefects. The effect of impurity atoms on magnetic relaxation is especially marked when the equilibrium state of the ferromagnetic is established after it has been demagnetized by an alternating magnetic field with decreasing amplitude, $H_\alpha \to 0$.

In this case, when the equilibrium state is established, there is a decrease in the magnetic permeability. This phenomenon of magnetic relaxation has come to be known as disaccommodation of the magnetic permeability (DMP). The temporary variation of the magnetic permeability may be of shorter or longer duration, depending on the specific character of the redistribution of the boundary layers between the regions of spontaneous magnetization, corresponding to the most stable of their energy states.

In [4, 5, 12, 16, 17] it was shown that DMP is stronger in ferromagnetics which contain atoms of an impurity.

The specimens investigated contained silicon in concentrations ranging from tenths of a percent to 2%, while other impurities were present in the same, practically negligible, concentrations. To bring them into their original equilibrium state, the latter were subjected to vacuum annealing at a temperature of 900°C, at which there was practically no oxidation of the surface. The nonequilibrium magnetic state was brought about by demagnetization in an alternating magnetic field at a frequency of 50 Hz from a maximum amplitude $H_{max} = (5\text{-}8)\cdot 10^3$ A/m to a minimum value $H_{min} \to 0$ ($H_{min} < 10^{-1}\text{-}10^{-2}$ A/m) for a period of 5-7 sec. A special demagnetizing device was used to make sure that the magnetic field was practically uniform over the length of the specimen and that its amplitude decreased at the same rate to

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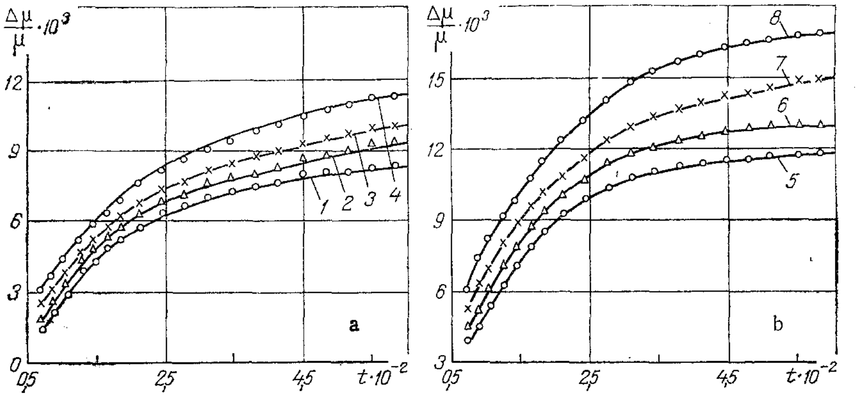

Fig. 1. Magnetic-relaxation curves for DMP in specimens of Fe with different concentrations of Si: a. 1) 0.21%; 2) 0.35; 3) 0.50; 4) 0.75. b. 5) 0.90%; 6) 1.22; 7) 1.63; 8) 1.94.

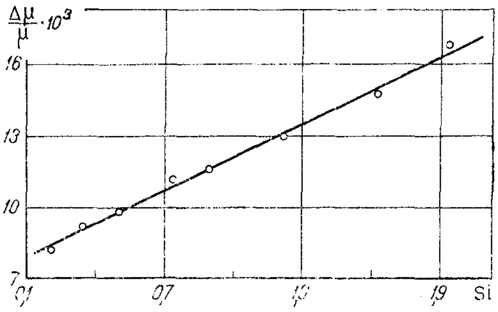

Fig. 2. Steady-state relaxation parameter (for t = $5.5 \cdot 10^2$ sec) of the investigated specimens as a function of the Si impurity atom concentration.

the minimum $H_{min} \to 0$. Maintaining this demagnetization regime guaranteed that the initial states for all the investigated specimens were approximately the same. These conditions are particularly important, since when a ferromagnetic attains the state $H_{min} \to 0$ and $J \to 0$, it is impossible to make sure every time that the regions of spontaneous magnetization will have the same distribution. Complete demagnetization ($H \to 0$, $J \to 0$) is attained in the general case with a large number of different arrangements of the regions relative to one another. Therefore, in bringing the specimens into a nonequilibrium state, we must maintain identical conditions during their remagnetization, in order that the initial distribution of the regions of spontaneous magnetization will be quasiidentical, to some degree of approximation.

The measurement of the temporary changes produced in the magnetic properties of specimens by DMP was carried out in a manner similar to that of [12]. The investigated specimen was the core of a coil in an oscillatory loop, and after increasing the frequency we determined the variation of the change in the magnetic permeability with time as a result of magnetic relaxation.

The relative change in the magnetic permeability is

$$\Delta\mu(t_0,\ t)/\mu(t) = \frac{\mu(t_0)-\mu(t)}{\mu(t_0)} = \frac{\nu^2(t)-\nu^2(t_0)}{\nu^2(t)},$$

where $\mu(t)$, $\nu(t)$; $\mu(t_0)$, $\nu(t_0)$ are the values of the magnetic permeability and the frequencies at a given instant of time and at the initial instant of time after the demagnetization.

For all the specimens investigated, we took magnetic-relaxation curves $\Delta\mu/\mu = f(t)$, characterizing the disaccommodation of magnetic permeability, at room temperature immediately after they had been demagnetized by the regime indicated above. Figure 1 shows these curves for Fe specimens with different concentrations of Si impurity atoms. From an analysis of these curves it is clear that the time-dependent variation of the magnetic properties of all the investigated specimens takes place with higher intensity at the initial stage of relaxation, slowing down at the subsequent stages and becoming practically stabilized from some moment on. The principal variation of the magnetic properties of the specimens, making up more than 80% of the steady-state value of the relaxation parameter, takes place practically in 15-18 sec. The character of the relaxation curves is identical for all the specimens with small differences between the numbers of silicon impurity atoms present. As the concentration of silicon impurity atoms becomes higher in the specimens, these curves have a tendency to move upward. The observed character of the development of the relaxation process in the transition of a ferromagnetic from the thermodynamically nonequilibrium state to steady-state equilibrium may be attributed to the fact that the rate of displacement of the domain boundaries varies at the different stages of its development. The domain boundaries do not take on their stable state immediately but become "stuck" each time at some new points. In the boundary layer, owing to the nonuniformity of the magnetization, there arise gradients in the magnetostrictive stresses, intensifying the diffusion of the impurity atoms in the crystal lattice. All of these phenomena lead to the redistribution of the stresses in a given region, which affects the character of the distribution of the energy barriers that form the various obstacles to the displacement of the domain boundaries.

Silicon impurity atoms in a bcc lattice cause a distortion of its cubic symmetry, resulting in a nonaxial elastic deformation, which in turn intensifies the increase in the steady-state relaxation parameters. As can be seen from Fig. 1, as the silicon impurity atoms become more numerous, the magnetic relaxation becomes more intense. Starting at $t > 9$-10 min, the process becomes practically stabilized and the changes in the magnetic properties take on their steady-state values.

Figure 2 shows how the steady-state relaxation parameter varies with the Si concentration in the specimens. It follows from the figure that a correlation exists between these parameters.

NOTATION

t, time; μ, magnetic permeability; ν, frequency; H, magnetizing field intensity; J, magnetization.

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