MAGNETIC AGING OF ELECTRIC SHEET


Low-carbon electric sheet is characteristically susceptible to magnetic aging, which impairs the operating properties of instruments. Magnetic aging is defined as the increase of the coercive force due to precipitation of nonmagnetic or weakly magnetic phases from the solid solution, preventing shifts of interdomain boundaries. Of greatest practical interest is low-temperature aging at 120°C, which is affected in particular by carbon and nitrogen, with low diffusion activation energies in iron. However, the experimental data indicate that the roles of carbon and nitrogen in the process of low-temperature magnetic aging differ.

We investigated the kinetics of magnetic aging of cold rolled low-carbon electric sheet produced at the Novolipetsk Metallurgical Factory and the effect of various factors on magnetic aging. The chemical composition of the steels is given in Table 1.

The steels were annealed at 870 ± 50°C for 12 h in vacuum (10⁻⁵ mm Hg) in an atmosphere of dry inert gas (95% N₂ + 5% H₂) and in the oxidizing atmosphere of a box. As can be seen from Table 2, the annealing procedure affects the carbon and nitrogen concentrations. The carbon concentration decreases substantially after box annealing, particularly that of heat 2 subjected to preliminary black annealing. Annealing in vacuum and in dry inert gas has little effect on the carbon concentration. The removal of nitrogen from the steel is most effective with vacuum annealing.

After annealing, the samples were aged at 120°C for 3-240 h. The magnetic aging process was investigated by measuring the coercive force and the microthermo-emf.

The coercive force was measured with the BU-3 ballistic apparatus on samples 200 x 20 x 2 mm. After measurements of the coercive force, samples 30 x 30 x 2 mm were cut from these same strips for measurements of microthermo-emf. The samples were electropolished in a solution of 50 ml of 30% hydrogen peroxide, 6 ml orthophosphoric acid, and 4 g oxalic acid.

The variation of the coercive force during aging (Fig. 1) indicates that magnetic aging is affected by the atmosphere in preliminary annealing. The samples were most intensively aged after box annealing and least aged after annealing in dry inert gas.

Analysis of the chemical composition after annealing in different atmospheres leads to the conclusion that nitrogen is the main reason for magnetic aging after box annealing, carbon after vacuum annealing, and nitrogen and carbon after annealing in a protective atmosphere. With equal concentrations of carbon in heats 1 and 2 after box annealing (see Table 2) the coercive force is larger for heat 1 in all stages of aging (Fig. 1a) due to the larger concentration of nitrogen in the steel (0.0140 and 0.0115%, respectively). In this case nitrogen has a larger effect on the increase of the coercive force than carbon, which can be

<table>
<thead>
<tr>
<th>Heat No.</th>
<th>C</th>
<th>N</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ca</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.009</td>
<td>0.014</td>
<td>0.007</td>
<td>0.14</td>
<td>0.19</td>
<td>0.020</td>
<td>0.005</td>
<td>0.10</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>0.013</td>
<td>0.008</td>
<td>0.08</td>
<td>0.16</td>
<td>0.024</td>
<td>0.009</td>
<td>0.11</td>
<td>0.06</td>
<td>0.03</td>
</tr>
</tbody>
</table>

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Fig. 1. Magnetic aging at 120°C with time for electric sheet previously subjected to box annealing (1), annealing in a protective atmosphere (2), and in vacuum (3) of 10^{-5} mm Hg: a) heat 1; b) heat 2.

Fig. 2. Variation of microthermo-emf with aging at 120°C for electric sheet previously subjected to box annealing (1), annealing in a protective atmosphere (2), and in vacuum (3) of 10^{-5} mm Hg: a) heat 1; b) heat 2.

TABLE 2

<table>
<thead>
<tr>
<th>Heat No.</th>
<th>Composition %</th>
<th>box C</th>
<th>inert gas C</th>
<th>vacuum (10^{-5} mm Hg)</th>
<th>C</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.004</td>
<td>0.014</td>
<td>0.005</td>
<td>0.014</td>
<td>0.007</td>
<td>0.0115</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>0.0115</td>
<td>0.005</td>
<td>0.0115</td>
<td>0.008</td>
<td>0.0088</td>
</tr>
</tbody>
</table>

After vacuum annealing following preliminary black annealing the coercive force increases slightly during aging (Fig. 1a). Thus, when the metal contains less than 0.005% N and less than 0.008% C the low-carbon steel is subject to magnetic aging.

It is known [1] that with increasing carbon concentrations the precipitation of nitrogen from the supersaturated solid solution is inhibited and the aging process is slowed down somewhat. This is evidently also responsible for the lower values of Hc in all stages of aging after heat 2 is annealed in a protective atmosphere.

The data obtained in measurements of the microthermo-emf also lead to certain conclusions concerning the mechanism and kinetics of magnetic aging. The variation of the microthermo-emf with aging time shows low and high points (Fig. 2), which indicates that the aging process occurs in several stages. With increasing nitrogen and carbon concentrations two peaks are visible on the microthermo-emf curves, which indicates that the aging process occurs in two stages. Due to the high diffusion mobility of nitrogen [1, 2] it is liberated in the first stage of aging. The redistribution of nitrogen in the solid solution leads to its accumulation at certain places in the crystal lattice, as the result of which the elastic energy of deformation increases, which also leads to an increase of the microthermo-emf [3]. Later, the nitrogen is precipitated from the solution in the form of nitrides, the solid solution moves toward the equilibrium condition, and the thermo-emf decreases (Fig. 2a, b). With time, carbon accumulates in separate micro-volumes of the material, and thus the distortion of the crystal lattice increases in these places, resulting in an increase of the microthermo-emf (second peak on the curve). The precipitation of carbon-containing phase from the solid solution reduces the distortion of the ferrite lattice, and the thermo-emf decreases.

The steel contains the smallest amount of nitrogen after vacuum annealing. The thermo-emf curves have only one peak, which occurs at longer aging times (Fig. 2b). In this case aging is due primarily to the presence of carbon in the steel. It can be seen from Fig. 2a that with large amounts of nitrogen in low-carbon steel the peak characterizing aging, depending on the carbon content, occurs after longer aging times. According to data in the literature [4], nitrogen facilitates diffusion of carbon. This evidently causes a shift of the second peak on the microthermo-emf curves toward longer aging times. In the first stage of aging (less than 6 h) carbon is precipitated along with nitrogen, and consequently the ferrite is less supersaturated with carbon, i.e., the motive force of the process decreases.

CONCLUSIONS

1. Nitrogen induces magnetic aging of low-carbon electric sheet to a greater extent than carbon.

2. Magnetic aging of low-carbon electric sheet occurs in two stages — the first stage is due mainly to precipitation of nitrogen from the α solid solution and the second stage to precipitation of carbon.