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THE ROLE OF THE MAGNETIC MACROSTRUCTURE IN HEAT LOSS IN TRANSFORMER STEEL

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Measurements have been made on the magnetic macrostructures in electrotechnical steel for various states of magnetization and degree of elastoplastic deformation.

Advances in electrical engineering and electronics have meant that the uses of electrotechnical steel have steadily extended. The output of this steel is now millions of tons a year. Some of the electrical energy required for magnetization reversal is dissipated as heat. Loss reduction is a difficult problem not only as regards the unified physical theory but also from the technical viewpoint [1-4]. No complete physical explanation has been given for all the losses in ferromagnetics on reversal.

There are certain additional or neglected losses, which make it difficult for metallurgists to design new high-grade ferromagnetic meterials.

This requires further research on reversal related to the crystal and magnetic structures, the internal stresses, and various other factors.

Magnetic metallography provides a means of examining the losses in a ferromagnetic material in relation to texture perfection, since it enables one to examine the domain structure changes during reversal. It has been shown to be possible to examine not only domain structures but also lattice defects [5-7] arising during elastoplastic strain. In [8-10], magnetization curves were used to explain the magnetic anisotropy in crystals of silicon iron, and ways were demonstrated of optimizing the losses in textured transformer steel.

The domain structures were examined at high magnification. However, it has been shown [11, 12] that the magnetic macrostructure can be observed with the unaided eye. In that case, the magnetic suspension is replaced by a finely divided dry ferromagnetic powder.

We have used the macrostructure in researching textured transformer steel given various mechanical and magnetic treatments; the steel contained 3% silicon. The specimens were cut as plates of 400 × 100 × 0.35 mm with surfaces close to (110) planes and with the rolling direction coincident with the [100] easy magnetization axis.

Each specimen was magnetized with two identical flat coils at its ends. The field directions coincided with the rolling ones. The middle part, between the coils, was magnetized fairly uniformly.

The macrostructure was examined with the dry powder, which may consist of fine iron filings, ferromagnetic γ-Fe_2O_3, or finely ground ferrite. The best results were obtained with ferrite powders. We used ones of grain size 50-100 μm. Higher contrast was provided by coating the specimen with a thin layer of white paint. The powder was sieved onto the specimen, and then light tapping revealed the figures.

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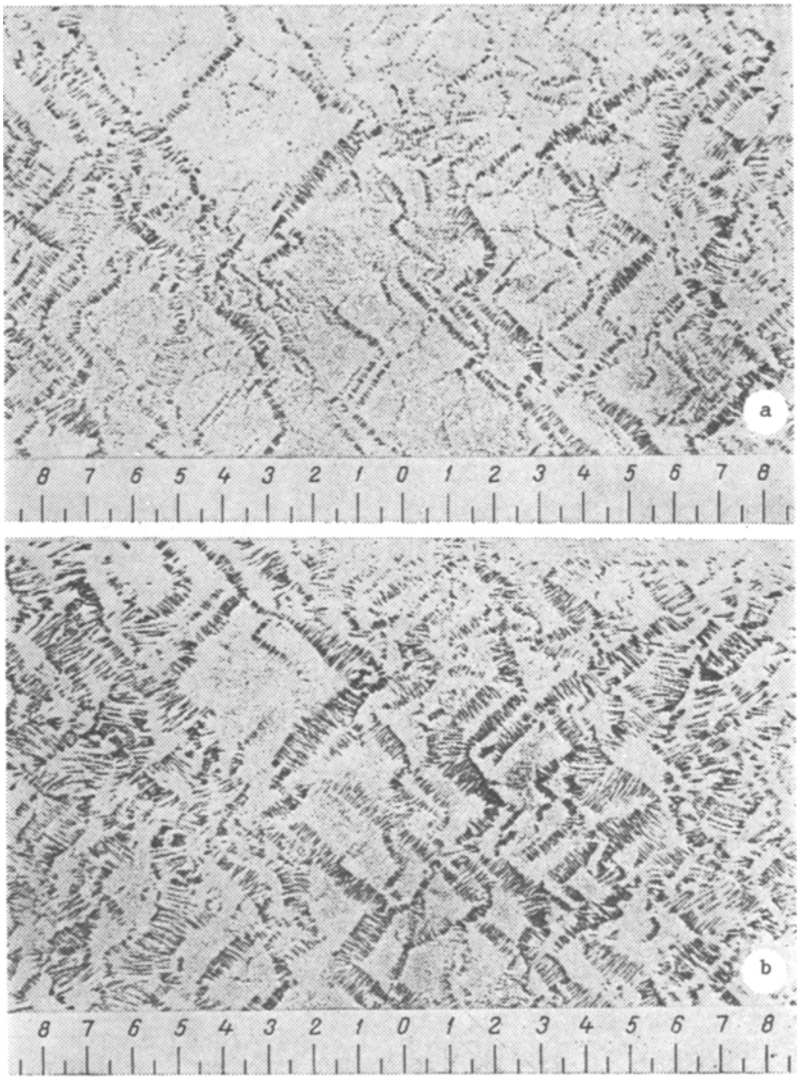

Fig. 1. Magnetic macrostructure in a uniformly magnetized specimen of electrotechnical steel in weak fields (a) and strong ones (b); the magnetizing field coincides with the rolling direction.

The elastoplastic strain was provided by stretching along the rolling direction.

Figure 1 shows structures in a specimen with various magnetizing fields; the figures are shown with a centimeter scale. The rolling direction and the field direction coincided and are denoted by **L** and **H**.

The patterns are fairly complicated, because of the crystal structure and the internal-stress distribution.

The bands are major elements in the figures, these consisting of approximately equally spaced lines perpendicular to the axes. The axes of the bands usually lie along the different direction, which is related to the texturing. The rectilinear parts of the zig-zag figures join up at angles of about 100-110°, while their inclinations to the rolling direction are 50-60°. The lengths ℓ of these segments vary from about 5 mm up to 40 mm or more.

On the whole, the powder figures do not alter in position and shape as the field increases up to saturation. At the start, the bands broaden somewhat (the striations enlarge), but afterwards the sizes remain constant.

The equilibrium state is influenced by external factors, and we examined these powder figures on stretching along the rolling direction in weak and strong fields. A specimen was uniformly stretched along the rolling direction and then coated with powder, after which the magnetizing field was switched on. The same technique was used as the stretching increases.

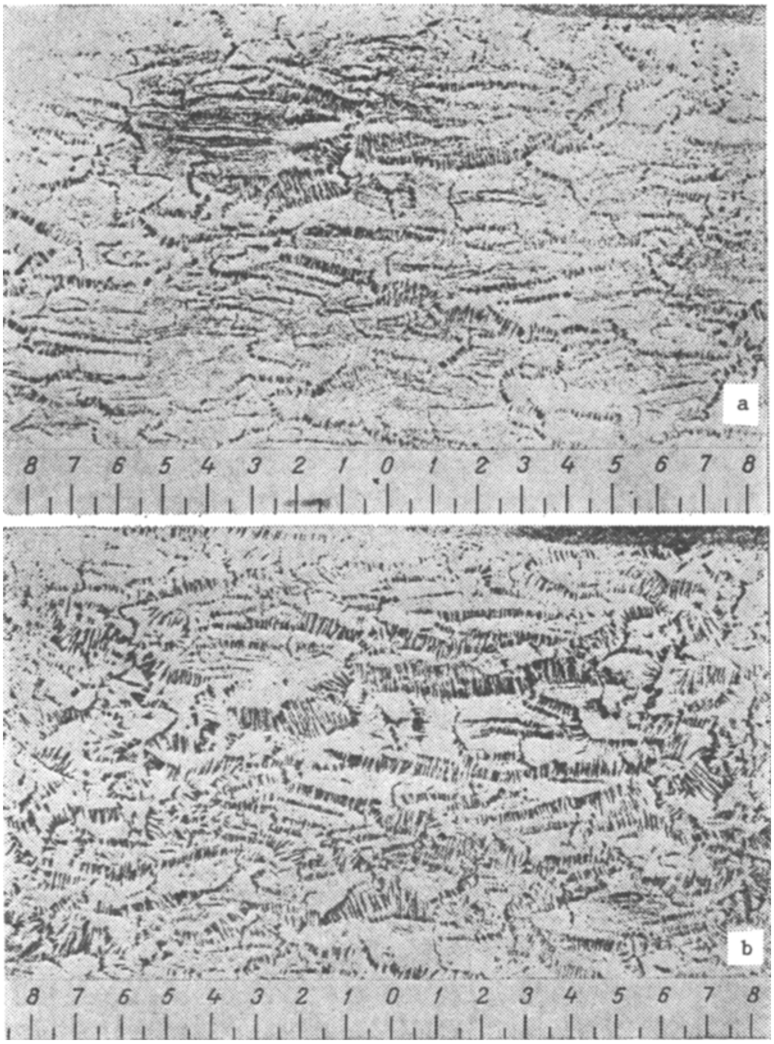

Fig. 2. Macrostructure in electrotechnical steel on stretching at $\sigma = 26\ kgf/mm^2$ in weak fields (a) and in strong ones (b); the magnetizing field, rolling direction, and stretching direction coincide.

Figure 2a shows structures in weak fields for $\sigma = 26\ kgf/mm^2$. The zig-zag pattern in the absence of stress (Fig. 1a) goes over to bands elongated on average along the stretching lines as the stress increases for weak fields, with the elongation tending to increase with the strain. The macrostructure becomes more uniform and more ordered, and also more uniformly distributed over the surface.

Figure 2b shows figures in a strong field for $\sigma = 26\ kgf/mm^2$.

Elastic tensile stresses disrupt the original zig-zag structure and favor the formation of bands along the rolling direction, the tendency increasing with the stress. At a given stress, the structure in strong fields differs from that in weak ones only in that the bands are broadened, while many of the characteristics remain the same.

Tensile stresses thus redistribute the macroscopic magnetic fields and produce new regions with reduced magnetic permeability oriented at comparatively small angles to the external field.

The number of bands, the widths, and the directions are related to structural inhomogeneity and give a statistical impression of the flux direction.

The topology and extent of this magnetic leakage provide scope for examining the energy dissipation as heat on account of the eddy currents occurring on reversal, as for example in transformers. Metallurgists and other researchers in recent decades have directed effort to improving the texture in electrotechnical steel, a characteristic feature being that the easy axes of the grains lie almost in the rolling plane. When a textured sheet is placed in a field directed along the rolling direction, the flux should be reasonably homogeneous, with the vector in the plane of the sheet. The heat loss is then due to eddy currents, which lie in the plane of the cross section. The leakage flux indicated by the powder (Figs. 1 and 2) indicates that there is an induction component normal to the plane of the sheet, which causes additional eddy-current losses [13]. In other words, the normal component due to the flux leakage complicates the eddy-current pattern considerably and is thus responsible for the additional loss.

NOTATION

σ, stress; H, magnetic field strength; L, rolling direction.

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