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Effect of cutting operation on core - loss of grain-oriented silicon iron

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Batches of Fe–3.25 wt % Si alloy with the (1 1 0) [0 0 1] texture and different nominal core-losses $P_{B,\nu}$ ($W\,kg^{-1}$), where B is the magnetic induction (T) and ν is the frequency (Hz), ($0.89 \leqslant P_{1.5,50} \leqslant 1.45$) were used to investigate the effect of cutting operation on the core-loss. It has been found that values for $P_{1,50}$ are greater than those for $P_{1.5,50}$, after both cutting and stress-relief annealing and are greatest when the material core-loss is least. Changes of core-loss after cutting are associated with stresses occurring in the cutting plane and in the adjacent volume of material, and the changes caused by stress-relief annealing are connected with the change of crystallographic grain orientation along the cutting edge from (1 1 0) to (1 1 1).

1. Introduction

The Fe–3 wt% Si alloy with the (1 1 0) [0 0 1] texture is a basic soft magnetic material used in the manufacture of transformer laminations for magnetic cores. This material should have a high magnetic induction, low core-loss and small magnetostriction. Attainment of these properties is mainly connected with the recrystallization texture, the level of non-metallic inclusions and harmful impurities [1, 2] and the state of stresses in superficial zones, obtained as a result of an appropriate selection of physical and chemical properties of the electro-insulating coating [3, 4].

Stresses applied to the material have a fundamental effect on the domain structure and, in consequence, magnetic properties and magnetostriction [1, 2, 5–7]. Compressive stresses have a negative effect within the whole range; tensile stresses, at least those of low magnitude, result in a reduction of unfavourably oriented domains and a lowering of magnetostriction, and therefore an improvement in magnetic properties.

The cutting operation involved in the manufacture of cores impairs, often to an unknown extent, magnetic properties, owing to deformation and development of stresses along the cutting edge. For this reason, in this work, an investigation was undertaken (a) to determine the effect of cutting Fe–3.25 wt% Si alloy with (1 1 0) [0 0 1] texture on the core-loss and (b) to establish causes leading to changes of its value after stress-relief annealing of the alloy.

2. Experimental procedure

Investigations were conducted on 80 specimens of grain-oriented transformer steel, showing different core-losses, $P_{B,\nu}$ ($W\,kg^{-1}$), where B is the magnetic induction (T) and ν is the frequency (Hz), such that $P_{1.5,50}$ ranged from 0.89 to 1.45 $W\,kg^{-1}$. Toroidal specimens with dimensions: inside diameter 70 mm, outside diameter 100 mm and length 30 mm were used. Specimens were prepared by coiling laminations, 160 mm in width, which, after annealing, were cut across the longitudinal axis of the core using rotary shears of diameter 200 mm.

Magnetic and metallographic investigations were made on specimens

(i) after the cutting operation;

(ii) after cutting and stress-relief annealing for 20 min in dry hydrogen at 1070 K; and

(iii) after grinding the deformed material layer along the cutting edge with emery papers.

Core-losses were measured at 50 Hz to within

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an accuracy of 1%. In order to reveal the macrostructure, the specimens were etched with a reagent composed of (by volume) 2 parts HNO_3, 2 parts H_2SO_4 and 10 parts H_2O. Examination of the microstructure was conducted on specimens etched with nital or, to reveal dislocations, the specimens were electropolished. Electropolishing was performed using an electrolyte composed of 190 ml of orthophosphoric acid with 30 g of chromic acid anhydride; a current density of 2.5 to 3 A cm^{-2} was used and the time of polishing was between 10 and 15 sec and then the specimens were electrolitically etched with Morris' reagent (133 ml of ice-cold acetic acid, 25 g of CrO_3, 7 ml of H_2O) for 2 to 3 min with direct current density of 0.1 A cm^{-2}.

Non-metallic inclusions were examined by using an optical microscope, X-ray microanalyser and a Quantimet 720-type microscope with image analyser.

Crystallographic grain orientation was determined on the basis of etch figures revealed by etching with acid containing 15 cm^3 50% H_2O_2, 50 cm^3 H_2O and 1 to 2 drops of HCl [8].

3. Results and discussion

Percentage variation of core-loss, $\Delta P/P$, is shown after cutting (Fig. 1a and c) and after cutting and stress relieving (Fig. 1b and d). It can be seen that core-loss after the cutting operation is considerably increased (Fig. 1a and c); $\Delta P/P$ for magnetic induction of 1 T and frequency of 50 Hz, $P_{1,50}$, and for magnetic induction of 1.5 T and frequency of 50 Hz, $P_{1.5,50}$, changes by 45 to 5% and by 35 to 3% at 1 and 1.5 T, respectively. The observed core-loss variation has not been eliminated but only lowered by stress-relief annealing (Fig. 1b and d; $\Delta P/P$ for $P_{1,50}$ and $P_{1.5,50}$ change by 20 to 3% and by 13 to 2%, respectively). In addition, Fig. 1 indicates clearly that changes of $P_{1,50}$ are greater than changes of $P_{1.5,50}$ and depend on the value of the sheet core-loss: the lower are these losses, the greater are the changes induced by the cutting operation. Examination of the microstructure shows that the increase in specimen core-loss immediately after cutting is associated with a considerable plastic deformation of material along the cutting edge. In the microstructure in the stressed region there is a high density of slip lines, this density decreasing gradually with the distance from the cutting edge along the specimen height, and then disappearing (see the microstructure shown in Fig. 2a). In sheets with a coarse-grained structure the slip lines, in particular, extend even

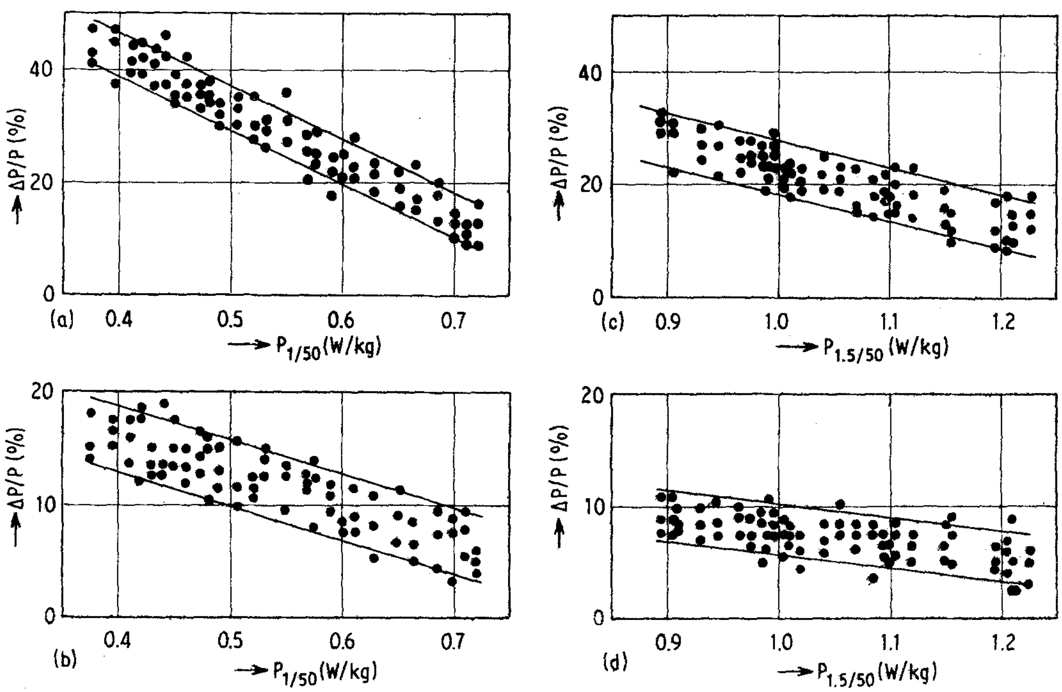

Figure 1 The dependence of core-loss changes $\Delta P/P$ of Fe–3.25 wt % Si alloy with (110)[001] texture (a and c) after cutting and (b and d) after cutting and stress annealing upon core-losses at magnetic induction of 1 T, at 50 Hz ($P_{1,50}$) and at 1.5 T at 50 Hz ($P_{1.5,50}$).

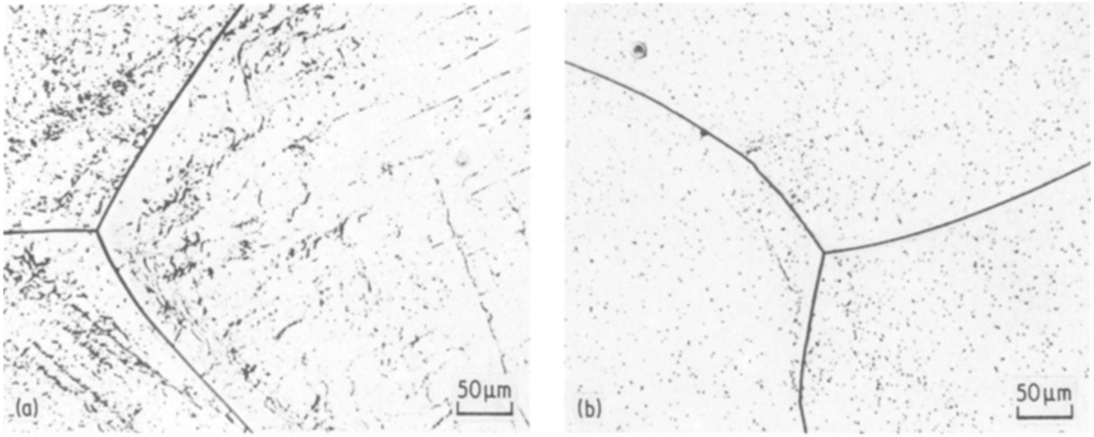

Figure 2 Dislocation structure of Fe–3.25 wt% Si alloy with (110)[001] texture and $0.4\,\mathrm{W\,kg^{-1}}$ core-loss at the magnetic induction of 1 T (a) after cutting and (b) after cutting and stress-relief annealing; the right-hand edge of the figure is 3 mm from the cutting edge.

as far as 7 mm from the cutting edge. Measurements of microhardness (Fig. 3), conducted to examine the dislocation structure, indicate clearly that the increase in core-loss is connected mainly with the stresses, occurring in the cutting edge and in the material volume in the close neighbourhood of the cutting edge, greatly hindering the material remagnetization.

Mechanical stresses in material are eliminated by a proper choice of heat treatment. Conditions of the stress-relief treatment used in this work were appropriate, as evidenced by homogeneous distribution of dislocations (Fig. 2b) and hardness, the latter corresponding to that of undeformed material in the deformation zone after annealing, see Fig. 3: compare respective curves, Curves a_1 and a_2 and Curves b_1 and b_2. In spite of that, the specimen core-loss continued to be elevated, as can be seen in Fig. 1b and d.

The macrostructure of specimens after stress-relief annealing (Fig. 4) reveals, along the cutting edge, an elongation of the grains in the direction perpendicular to the cutting edge; these elongated grains are visible in coarse-grained specimens (Fig. 4a shows core-loss at 1 T of $0.4\,\mathrm{W\,kg^{-1}}$) and particularly in fine-grained specimens (Fig. 4b shows core-loss at 1 T of $0.4\,\mathrm{W\,kg^{-1}}$. The etch figures of these grains (see Fig. 5a) have shown

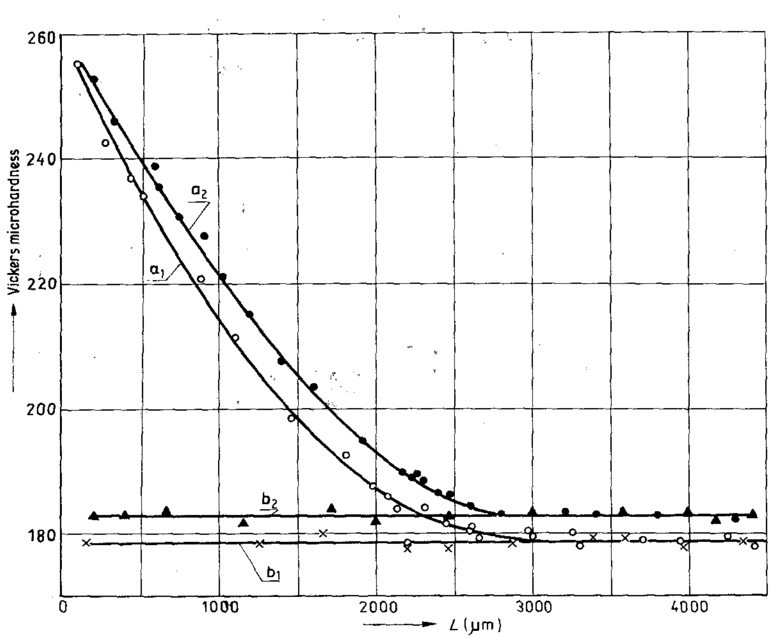

Figure 3 Vickers microhardness variation of Fe–3.25 wt% Si alloy with (1 1 0) [0 0 1] texture and core-loss at 1 T for (Curves a_1 and b_1) $0.4\,\mathrm{W\,kg^{-1}}$ and (Curves a_2 and b_2) $0.7\,\mathrm{W\,kg^{-1}}$, depending on the distance L from the cutting edge; after cutting (Curves a_1 and a_2) and after cutting and stress-relief annealing (Curves b_1 and b_2).

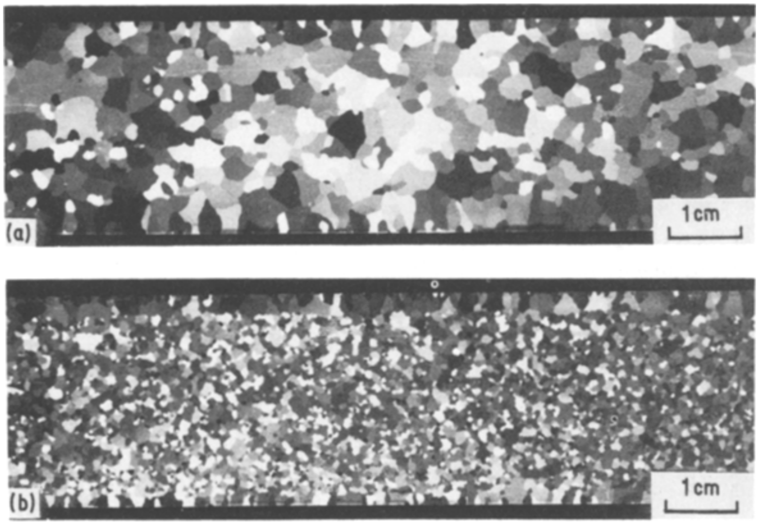

Figure 4 Macrostructure of Fe–3.25 wt% Si alloy with (1 1 0) [0 0 1] texture and (a) $0.4\,W\,kg^{-1}$ and (b) $0.7\,W\,kg^{-1}$ core-loss at magnetic induction of 1 T after cutting and stress-relief annealing. (Black lines = cutting edges).

that the grains have (1 1 1) orientation. By grinding a core layer of about 4 mm in depth, a zone of grains with (1 1 1) orientation has been eliminated (see the etch figures in Fig. 5b).

An analysis of the sheets under investigation revealed that the most numerous non-metallic inclusions present were silicate inclusions; these are generally aluminium silicates with simple chemical composition and minor Fe-contents. In addition to these simple silicates, there were occasionally identified more complicated silicate inclusions containing other elements, such as calcium, aluminum, titanium, iron and magnesium. Besides the silicate inclusions some sulphide inclusions were found, low in number, and also some calcium aluminates and aluminium oxides. The total inclusion level (varying, depending on core-loss, from 0.027 to 0.098 vol% for sheets with the lowest and the highest core-loss, respectively), and the nature of non-metallic inclusions did not change during the stress annealing. Thus, the core-loss variation after the stress relieving as observed in Fig. 1b and d, cannot be related to a change in the nature and amount of non-metallic inclusion due to heat treatment, as suggested by Kazadjan *et al.* [9]. Such an opinion will be correct only when the heat-treatment conditions favour the process of deep oxidation of sheets, i.e., the process of oxide inclusion formation. Our earlier investigation [10] showed the particular unfavourable influence on magnetic properties of inclusions of $n\mathrm{SiO_2} \cdot m\mathrm{Al_2O_3} \cdot l\mathrm{FeO}$-type, which, depending on the SiO_2 content, generates stresses that break the domain walls or develop a labyrinth domain structure around the inclusion. In accordance with the results of this work, it should be assumed that the observed changes of core-loss after cutting and stress-relief annealing are caused by an unfavour-

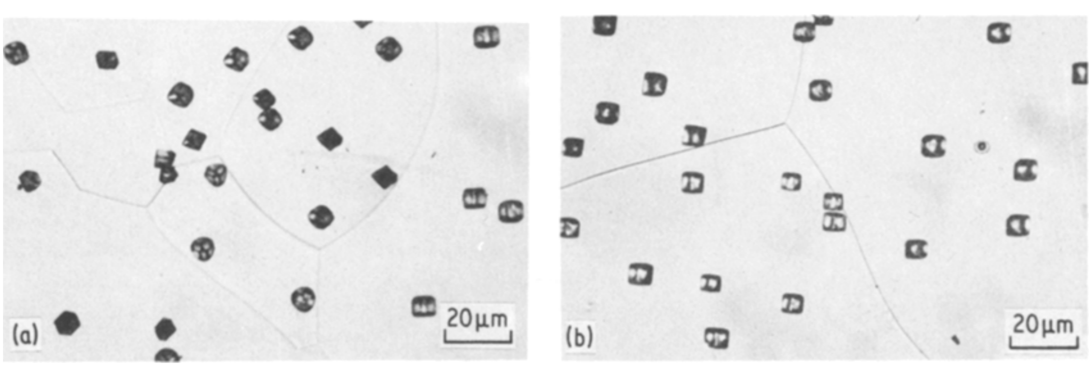

Figure 5 Etch figures of grains of Fe–3.25 wt% Si alloy with (1 1 0)[0 0 1] texture and $0.4\,W\,kg^{-1}$ core-loss at magnetic induction of 1 T after (a) cutting and stress-relief annealing and (b) grinding 3 mm layer form the cutting edge; the right-hand edge of the figure is 3 mm from the specimen cutting edge.

able, in a magnetic sense, crystallographic orientation of grains along the cutting edge.

In view of this investigations, greater changes in core-loss due to cutting in sheets with lower core-loss (e.g., for $P_{1,50} = 0.4\,\mathrm{W\,kg^{-1}}$) than occur with sheets of high initial core-loss (e.g., for $P_{1,50} = 0.7\,\mathrm{W\,kg^{-1}}$) are understable. Considering the fact that the amount of non-metallic inclusion in sheets of low core-loss is very low, and that the magnetic properties are determined mainly by (1 1 0) [0 0 1] texture, the appearance of grains of (1 1 1) orientation in the texture will result clearly in an increase of core-loss. Grains with the (1 1 1) orientation will have no greater effect on the magnetic properties of sheets with high core-loss, because the texture of these strips, contains, besides the (1 1 1) [0 0 1] texture, numerous components which are unfavourable in magnetic sense and, besides, the level of non-metallic inclusions in these sheets is usually higher.

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