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THE INFLUENCE OF COPPER ON THE MICROTEXTURE OF Fe-Si-Al ALLOYS FOR NON-ORIENTED ELECTRICAL SHEETS

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The effect of copper content in the range of 0,01 - 0,6 wt.% on the microtexture of some Fe-Si-Al non-oriented electrical sheets containing several impurity elements was investigated. The sheets were laboratory-manufactured and industrial samples of non-oriented electrical steels, decarburized and recrystallized, before the final annealing. Using the EBSD (electron backscatter diffraction) the microtexture was determined. It was found that the microtexture of the alloys containing more copper had fewer crystal grains with easy direction of magnetization in the sheet rolling plane. It was concluded that copper has a negative influence on the magnetic properties of soft-magnetic steel sheets.

Key words: *microtexture, non-oriented electrical sheets, copper*

Utjecaj bakra na mikroteksturu slitina Fe-Si-Al za neorijentirane elektrolimove. U radu se opisuje utjecaj bakra u rasponu od 0,01 do 0,60 mas.% na mikroteksturu slitina Fe-Si-Al, koje posjeduju i nečistoće. Ispitivani su bili uzorci razugljičenih i rekristaliziranih neorijentiranih elektro limova laboratorijske i industrijske proizvodnje, prije konačne toplinske obrade. Pomoću EBSD metode (electron backscatter diffraction) izvedena je analiza mikrotekstura limova, koja pokazuje, da mikrotekstura sa više bakra posjeduje manje kristalnih zrna u smijeru lake magnetizacije. Utvrđeno je, da bakar pogoršava magnetna svojstva meko magnetnih limova.

Ključne riječi: *mikrotekstura, neorijentirani elektrolimovi, bakar*

INTRODUCTION

The permeability and the power losses are very important properties of non-oriented electrical sheets. The existence of a crystallographic easy magnetization plane and direction makes the distribution of grain orientations (texture) the most important factor in the improvement of the quality of a soft magnetic material [1]. The optimum texture is a fibre texture in which all the grains have a <100> direction normal to the sheet plane. The ideal texture for non-oriented electrical sheets is {100}<0*vw*>, because it ensures the presence of the maximum number of easy magnetization planes and the isotropy of the magnetic properties in the plane of the metal sheet [1 - 3]. The magnetic properties of less well textured non-oriented electrical sheets are not as good as those of grain-oriented sheets with a Goss texture {110}<001>, which makes them better suited for use in rotary magnetic fields [4]. The <100> crystallographic direction is the direction of easiest magnetization, and if the sheet is magnetized in the rolling direction, a very high permeability and a very low coercive force are obtained [4].

For electrical sheets, different methods of texture measurement and presentation are possible. To determine the surface distribution of a smaller area the SEM Kikuchi method of electron backscatter diffraction (EBSD) can be used [5]. The back-scattered electrons from the tilted specimen form the Kikuchi diffraction patterns, which are then transferred to a screen, digitised and analysed by comparing with low-index Kikuchi patterns. EBSD microtexture determination is now a fully automated procedure that can be performed in a scanning electron microscope. The term microtexture integrates both, the crystallographic parameters and other aspects of the microstructure, and it also describes the experimental technique used to determine this information [6].

EXPERIMENTAL WORK

Samples of copper-containing laboratory-manufactured and of industrial non-oriented electrical sheets were used in the investigation. The chemical compositions of

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the alloys are presented in Table 1. A laboratory alloy with a very small content of copper (0,01 %) was used for the comparison. The vacuum-melted alloys were cast into ingots and then hot and cold rolled into a sheet with a thickness of 0,5 mm.

Table 1. **Chemical composition of the Fe-Si-Al alloys (wt. %)**
Tablica 1. **Kemijski sastav slitina Fe-Si-Al (mas. %)**

Alloy	%Fe	%C	%Si	%Al	%Mn	% P	% S	%As	%Cu	%Sb	%Sn
LAB0	balance	0,042	1,73	0,80	0,20	0,002	0,002	<0,001	0,01	0,0004	0,005
LAB1	balance	0,011	1,90	0,55	0,24	0,005	0,005	<0,001	0,24	0,0004	0,005
LAB2	balance	0,009	1,86	0,46	0,24	0,005	0,005	<0,001	0,43	0,0006	0,003
IND1	balance	0,023	1,68	0,24	0,24	0,010	0,002	0,010	0,33	0,0050	0,019
IND2	balance	0,022	1,74	0,47	0,26	0,021	0,002	0,006	0,60	0,0092	0,027

The samples were then annealed for decarburization and recrystallization. Prior to heat treatment, the samples were metallographically ground and polished, and then heated in nitrogen and decarburized in a wet hydrogen gas mixture (H_2O/H_2) for 15 minutes at 840 °C. The recrystallization annealing was performed afterwards at 980 °C in dry hydrogen.

EXPERIMENTAL RESULTS

The microtextures of the sheets were determined on the surface of 0,5-mm-thick samples after the decarburization and recrystallization annealing. The maximum volume fraction of crystal grains with their {001} plane parallel to the sheet plane was found in the alloy with the lowest amount of copper (Figure 1.).

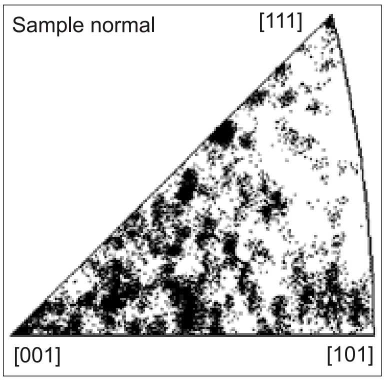

Figure 1. **Inverse pole figure for the laboratory non-oriented electrical steel with 0,01 % Cu**
Slika 1. **Inverzna polova slika laboratorijskog neorijentiranog elektrolima s 0,01 % Cu**

The ideal texture for non-oriented electrical steel sheets is {100}<0*vw*>, because it ensures the maximum number of easy magnetization directions in the sheet plane [1 - 4, 7].

Figures 2. - 5. show the inverse pole figures for the non-oriented electrical steel sheets containing 0,24, 0,33, 0,43 and 0,60 % of Cu. The inverse pole figure is a single unit triangle of a stereographic projection that shows one type of lattice plane normal [5].

The highest density of crystal grains close to the {111} lattice plane parallel to the steel sheet was present in all the alloys containing copper (Figures 2. - 5.).

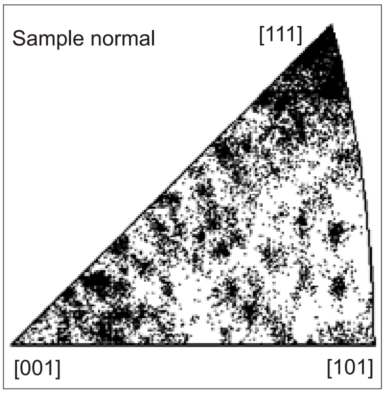

Figure 2. **Inverse pole figure for the laboratory non-oriented electrical steel with 0,24 % Cu**
Slika 2. **Inverzna polova slika laboratorijskog neorijentiranog elektrolima s 0,24 % Cu**

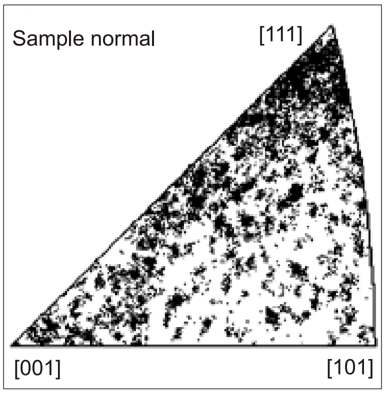

Figure 3. **Inverse pole figure for the laboratory non-oriented electrical steel with 0,43 % Cu**
Slika 3. **Inverzna polova slika laboratorijskog neorijentiranog elektrolima s 0,43 % Cu**

A visual assessment shows that the density of hard planes is similar across the whole range of copper content. If the density of hard lattice planes in the sheet rolling plane was directly related to the content of copper, a significant difference would be expected between the sheet containing 0,24 % Cu and the sheet containing 0,60 % Cu, for example. Since this was not the case, it is concluded that the effect of copper on the texture is indirectly related to its content in the steel. A logical explanation is that the effect of copper is related to its surface segregation, and in fact, a

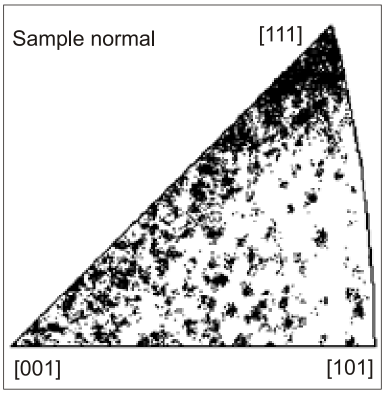

Figure 4. **Inverse pole figure for the industrial non-oriented electrical steel with 0,33 % Cu**
Slika 4. **Inverzna polova slika industrijskog neorijentiranog elektrolima s 0,33 % Cu**

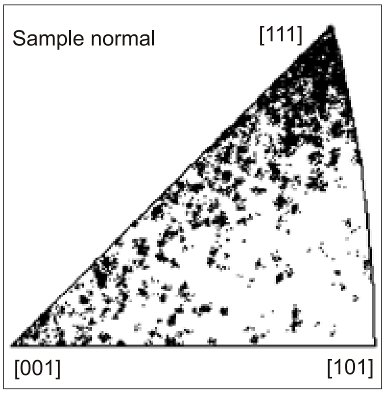

Figure 5. **Inverse pole figure for the industrial non-oriented electrical steel with 0,60 % Cu**
Slika 5. **Inverzna polova slika industrijskog neorijentiranog elektrolima s 0,60 % Cu**

considerable surface segregation was established using Auger electron spectrometry (AES) on specimens containing 0,24 to 0,60 % Cu [8]. Figure 6. shows the results of this analysis and confirms a significant surface segregation of copper.

The maximum amount of surface segregation of copper was found in the temperature range of the recovery of the cold-rolled steel sheets, and a considerable level of that segregation is also present in the temperature range of recrystallization.

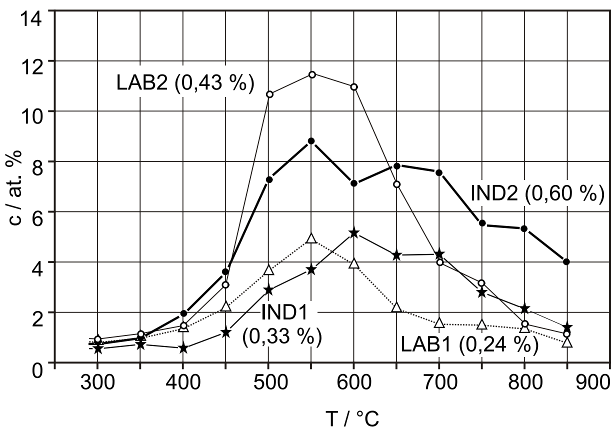

Figure 6. **Surface segregation of copper in non-oriented electrical sheets**
Slika 6. **Površinska segregacija bakra u neorijentiranim elektrolimovima**

On the basis of these results it is concluded that the surface segregation of copper inhibited either the formation of the nuclei of crystal grains with the soft lattice plane (001) or (011) in the sheet plane or the growth of such nuclei when already formed.

Table 2. **Grain size of the non-oriented electrical steel sheets after heat treatment**
Tablica 2. **Veličina zrna neorijentiranih elektrolimova nakon toplinske obrade**

	LAB0	LAB1	LAB2	IND1	IND2
Grain size / μm	62,6	53,4	45,4	46,9	51,3
Copper content / wt. %	0,01	0,24	0,43	0,33	0,60

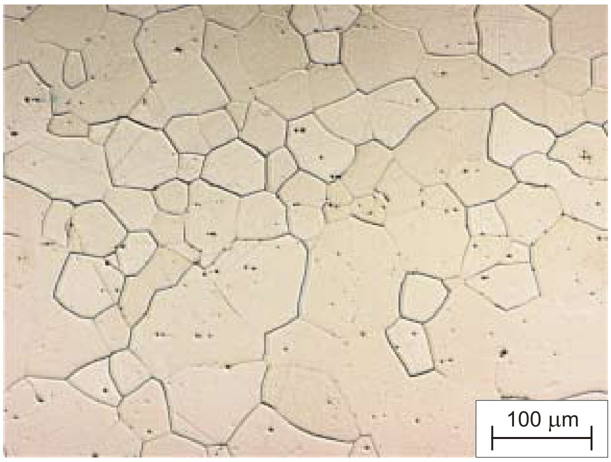

Figure 7. **Microstructure of the laboratory non-oriented electrical steel containing 0,43 % Cu (mag. 100-times, etchant: Nital)**
Slika 7. **Mikrostruktura laboratorijskog neorijentiranog elektrolima s 0,43 % Cu (100×, nagrizano Nitalom)**

The microstructures of the samples of non-oriented electrical steels after heat treatment consisted of polyhedral ferrite grains (Figure 7.).

As shown in Table 2., after an identical heat treatment the grain size was coarser in the alloy containing a very small amount of copper (0,01 % Cu) than in the alloys containing 0,24 % Cu or more.

DISCUSSION

It is known that the segregation of surface-active elements induces a selective growth of grains; it decreases the surface energy of certain crystal grains releasing the elastic energy of the lattice [7]. In non-oriented electrical steels a positive effect on texture development has been achieved by alloying with some surface-active elements, like antimony [9, 10] or tin [11]. The content of copper as an impurity element in these steels is increasing due to the repeated recycling of scrap steel. The presence and segregation of copper does not have a beneficial effect on the formation of the texture of the non-oriented electrical steel sheets, since, the crystal grains with orientation {111}<*uvw*> are predominant in the sheets containing from 0,24 to 0,6 % Cu, as was evident from the microtexture measurements. In the texture optimization of non-oriented electrical steels the crystal grains with orientations such as {111}<*uvw*> or {211}<*uvw*> in the sheet plane should be avoided, because they have planes without easy magnetization direction. They should be replaced by crystal grains with {100} or {110} planes parallel to the plane of the steel sheet.

Generally, alloying elements with a propensity to surface segregation also segregate on the grain surface forming intergranular segregation [12].

It is assumed that the smaller grain size in the alloys containing copper might be related to copper grain-boundary segregation, in spite of the fact that it was not possible to obtain an intergranular fracture to verify this assumption. The transgranular nature of the fractures is evidence that the grain-boundary segregation of copper does not decrease the grain-boundary cohesion in these alloys sufficiently to induce an intergranular fracture. It is also possible that the grain growth in copper-containing steels is inhibited by the precipitation of copper from solid solution, since, the solubility of copper in ferrite is approximately 0,1 wt. % at 500 °C, and increases to its maximum value of 2 wt. % at 857 °C [13].

In a recent study [14] it was found that the decrease of the initial carbon content after decarburization annealing was the highest in the laboratory Fe-Si-Al alloy with the lowest amount of copper. However, the residual content of carbon in solid solution of ferrite after decarburization was virtually equal for 0,01 % Cu and 0,43 % Cu [14]. It was concluded that in the investigated range from 0,01 to 0,43 % copper it does not have a significant effect on the total decarburization efficiency of the silicon-aluminium steel for non-oriented sheets.

CONCLUSIONS

The effect of copper content on the microtexture of non-oriented electrical sheets was investigated.

With EBSD (electron backscatter diffraction) the microtexture of Fe-Si-Al alloys with copper contents in the range from 0,01 to 0,60 % was determined. In the steel sheets with 0,01 % Cu the density of the crystal grains with the lattice plane (100) in the sheet plane was the highest, while, in the sheets containing copper the density of the (111) plane was the highest. The (001) plane is the plane of easiest magnetization and change of magnetization direction. A high density of grains with the lattice plane (001) in the sheet plane is, therefore, beneficial for the quality of soft-magnetic alloys, while the effect of a high density of (111) crystal grains in the sheet plane has the opposite effect.

For this reason it is concluded that the presence of copper in soft-magnetic Fe-Si-Al steels has two negative effects: non-magnetic copper atoms decrease the saturation magnetization of the sheets, and the high density of grains with the (111) lattice plane parallel to the sheet plane decreases the permeability and increases the energy necessary for the change of magnetization direction.

The presence of copper does not affect the residual content of carbon in solid solution in ferrite of the decarburized sheet, while, with increasing copper content, the grain size is smaller after identical recrystallization annealing.

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