INVESTIGATION OF GRAIN BOUNDARY MOTION IN DEPENDENCE OF APPLIED DEFORMATION VALUE

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SLEDOVANIE POHYBU HRANÍC ZŔN VPLYVOM VEĽKOSTI APLIKOVANEJ DEFORMÁCIE

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Abstract

In spite of many decades of research and continuous improvement of the quality of electrical steel we still cannot be satisfied today with processing cost as well as the magnetic properties of the commercial products [1]. The improvement of magnetic properties of electrical steel concerns many metallurgical aspects: microstructural features such as grain size, crystallographic texture or inclusions are important. Grain growth together with precipitation is fundamental processes of microstructural and textural evolutions taking place during the thermo-mechanical processing of electrical steels [2]. They are of major scientific interest and presents great importance in a wide range of industrial applications.

The present paper is aimed to investigate of grain growth processes induced by gradient of generated deformation in grain oriented electrical steels (GO). Dynamic grain boundary motion was investigated by difference of deformation value that was generated on the experimental steel. The gradient of deformation in materials was carried out in cross section of the investigated steels. The mentioned gradient was obtained by hardness testing machine. The value of deformation gradient inside of material was changed because of external stress that was carried out by force load tools of the hardness tester. This work is an investigation of the influence of different intensity of deformations on grain growth taking place exclusively in one sample. The obtained experimental results were realized to deeper understanding of grain growth phenomena in the grain oriented electrical steels.

Key words: grain oriented electrical steels, grain boundary motion, deformation gradient

Abstrakt

Napriek desaťročiam výskumu a neustáleho zlepšovania kvality elektro ocelí, ešte stále nemôžeme byť spokojní s výrobnými nákladmi, ako aj magnetickými vlastnosťami komerčných produktov [1]. Zlepšenie magnetických vlastností elektro ocelí sa týka mnohých metalurgických aspektov, dôležité sú mikroštruktúrne vlastnosti ako veľkosť zrna, kryštalografická textúra alebo inklúzie. Rast zrna spolu s precipitáciou sú základné procesy

mikroštruktúrneho a textúrneho vývoja počas termo-mechanického spracovania elektro ocelí [2]. Sú hlavným vedeckým záujmom a majú veľký význam pre množstvo priemyselných aplikácií.

Táto publikácia je zameraná na sledovanie procesov rastu zrna vyvolaných gradientom deformácie vytvorenej v zrnovo-orientovaných elektro oceliach (GO). Sledoval sa dynamický pohyb hraníc zŕn v závislosti na rozdielnom stupni deformácie aplikovanom na experimentálnej oceli. Gradient deformácie v materiáli bol meraný po priečnom priereze sledovaných ocelí. Jeho hodnoty boli získané pomocou merania tvrdosti. Veľkosť gradientu deformácie vo vnútri materiálu sa menila vplyvom vonkajšieho napätia vyvýjaného na materiál pomocou tvrdomera . Práca sa zaoberá výskumom vplyvu rôznej intenzity deformácie na rast zrna, ktorý nastal výlučne v jednej vzorke. Získané experimentálne výsledky majú poslúžiť lepšiemu pochopeniu javu rastu zrna v zrnovo-orientovaných elektro oceliach.

1. Introduction

The total electric energy generation and a large part of the electricity consumption are relevant to rotating machines and transformers. Any improvement in their specifications could represent a great economic interest. One possible way to approach this goal is to use a convenient magnetic material for the machine core, i.e. a material with better efficiency [3, 4]. Grain oriented electrical steels belong to the soft magnetic materials. These kinds of steels are used as core materials in different types of transformers [5]. From a technological point of view, the properties of the grain oriented steels are depended on the microstructural and substructural states, i.e. grain size, grain morphology, density of crystallographic defects, preferable crystallographic orientation, chemical composition of the solid solution and presence of secondary phase particles as well [6]. Properties of GO steels are closely connected with grain growth processes. Grain size of the final microstructure is important engineering parameter which influences the material properties such as magnetic properties, yield strength etc. Moreover, it is important to control not only the final microstructure of electrical steels but the texture state in the final material [7]. Hence, taking into account the directional anisotropy of physical properties in crystallographic lattice of ferrite (bcc) and the fact that GO steels are mainly used in linear electromagnetic field (i.e. in electrical transformers) it is necessary to provide crystallographic anisotropy in the plane of sheet parallel to rolling direction in order to achieve good final magnetic properties. This crystallographic anisotropy can be provided by [110]{001} or by so called Goss texture [8].

Kinetic of grain boundary motion influences the formation of the final microstructure and texture that in turn have direct impact on the final magnetic properties. The investigated GO electrical steels are subjected to different types of thermo-mechanical processes to investigate kinetic of grain boundary motion. The grain size in the treated materials revealed to be very dependent on stored energy in the grains.

It is well know that, stored energy accumulated in the material after applied deformation has the following form [9, 10]:

$$P = \frac{1}{2}\rho\mu b^2 \tag{1}$$

where ρ is dislocation density (~ 10^{15}m^{-2}), μ chemical potential and b the dislocation Burgers vector. Application of different combinations of deformation and annealing temperature play an important role in study of grain boundary motion mechanisms. The influence of mechanical deformation on the grain growth phenomena was investigated in this paper. The gradient deformation was generated in each investigated sample to follow grain growth kinetic within one sample.

2. Experimental procedure

GO electrical steel taken from industrial line after first step of cold rolling and subsequent decarburization annealing was used as an experiment material within the present work. The surface of the materials was indented by different loads made by hardness tester ball which leads to concentration of stress in small volume of samples. There were used four values of loads that lead to four different generated deformations intensities on the investigated steel. The generated deformation intensities were controlled by diameter of indented ball and value of loading force applied to the ball of the hardness tester. The principle scheme of deformation generation by ball of hardness tester machine is show in Fig. 1,

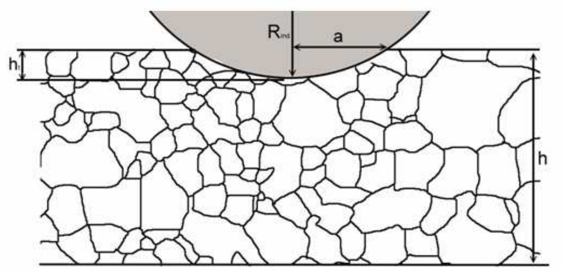

Fig.1 Scheme of the primary zone of deformation generation for spherical indentation

where a - radius of indentation, R_{ind} – radius of ball and h_t – maximum depth of impress. Parameters of process such as indentation, d – diameter of balls, F– loaded force on the ball and ε – value of impress deformation, are showed in Table 1.

The chemical conception of the experimental material is presented in Table 2. The thickness of the investigated steel is d = 0.65 mm. The material was subjected to laboratory annealing at temperature 900°C for 120 seconds. The annealing atmosphere was pure hydrogen (d.p. ~ -23 °C).

Table 1 Parameters of indentations applied to the investigated materials in order to generate different deformation intensities

	F = 613N	F = 306.5N
d = 2.5mm	ε = 6.8%	ε = 3.8%
d = 5mm	ε = 4.5%	ε = 2.2%

The heat treatment was realized with furnace "Nabertherm" equipped with an electronic control system C19/S19. The microstructure of the investigated specimens was examined in cross section plane parallel to rolling direction. The texture of laboratory treated samples was measured in the same section by means of EBSD method. The JEOL JSM 7000F FEG scanning electron microscope was employed to perform the texture analysis. Patterns formed from back scattered electrons were detected by "Nordlys-I" EBSD detector. The obtained EBSD data were analyzed and displayed by CHANNEL-5, HKL software package.

The humidity of the annealing atmospheres was measured by “Optidew” system with “High Performance Optical Dew-Point Transmitter” from “Michel Instruments”.

Table 2 Chemical composition of the investigated steel (in wt. %)

Material	C, %	Mn, %	Si, %	P, %	S, %	Al, %l	N, %
	0.0056	0.21	3.15	0.07	0.009	0.013	0.011

3. Results and discussion

The microstructure obtained after laboratory treatment of the investigated material is presented in Figs. 2. As one can see, impress is localized in small field near the sample surface. Generated in this way strain allowed to follow grain growth progress in surface area where the impress was applied after applied annealing process. The dependence of grain boundary motion on generated deformation stress one can follow in the Fig. 2**.**

As one can see in Fig. 2 there are different types of microstructure developed after application of different impress deformation and subsequent annealing at 900ºC for 2 min. It is interesting to note that, these series of experimental samples have a precise line of distinction among themselves. As one can see, the fraction of small grains (grain size ~ 12 µm) is about ~70% of the total area of sample. It is an area where the process of second recrystallization has been not started. The grain size of the huge grains is about 200 – 500 µm. The fractions of these grains are about ~ 30% of the total area of the sample. Moreover, all the huge grains are located near the surface of the sheet plane with deformation impress.

As one can see from the Fig. 2a and Fig. 2d, the regions with huge grains in both pictures are completely different near the deformation impress. In the first case, deformation of

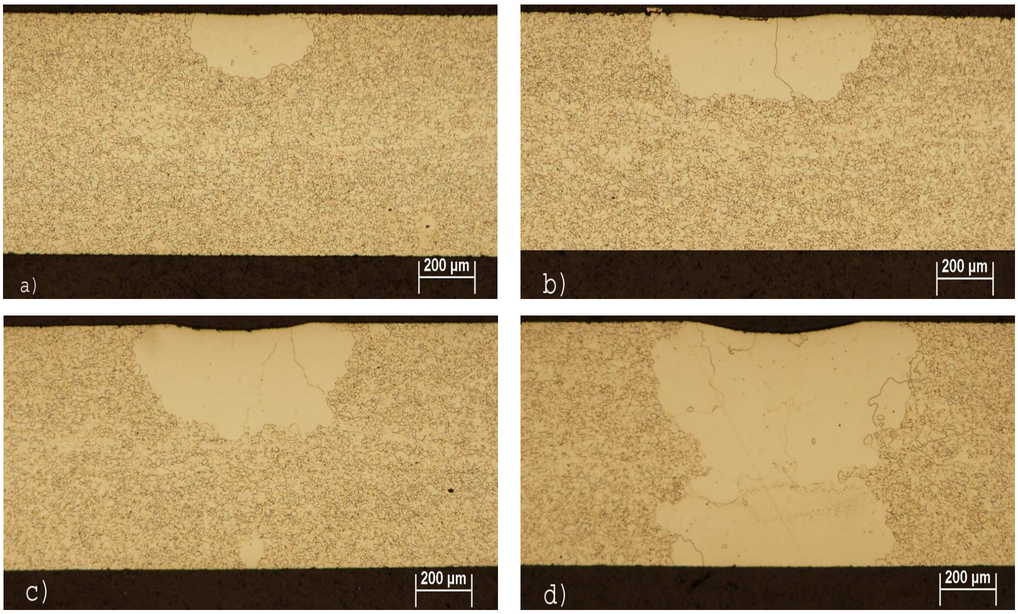

Fig.2 Sample of the investigated steel with: a) ~ 2,2%, b) ~ 3,8%, c) ~ 4,5%, d) ~ 6,8% impress deformation, annealed at 900ºC for 2 min in pure hydrogen atmosphere (d.p.~-23ºC).

about ε~ 2.2% was applied, the grain size of the huge grain is ~ 350µm, see Fig.2a the grain growth near the area of applied deformation. The sizes of these grains are match bigger than the

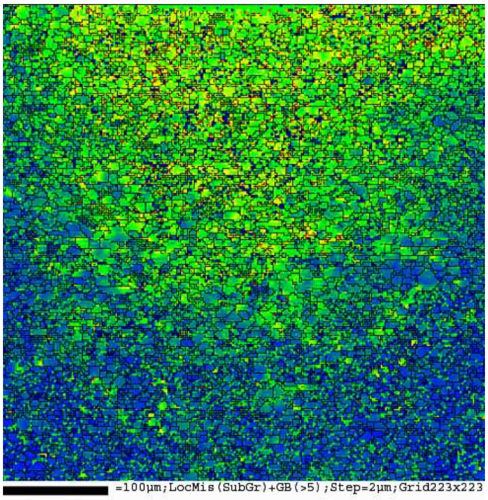

Fig.3 Local misorientation map obtained from EBSD analysis of the investigated sample with impress deformation.

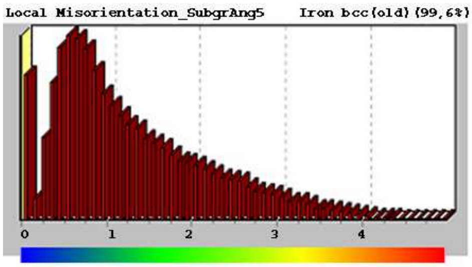

Fig.4 Local misorientation distribution of the microstructure shown in the Fig. 3

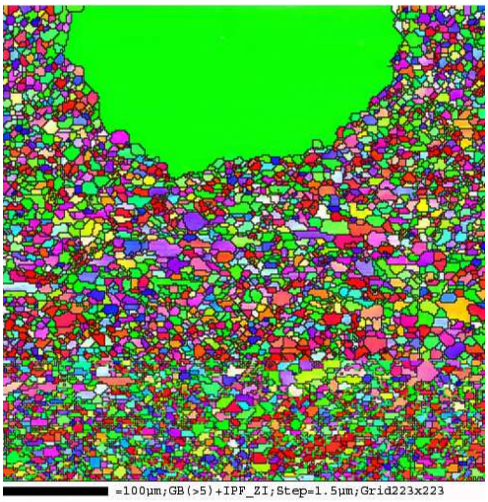

Fig.5 IPF map of the investigated sample after application of impress deformation of ε~2.2% and heat treatment at 900ºC for 2 min.

size of surrounding grains. The mentioned grain growth features leads one to suggestion of abnormal grain growth character of grains located near the surface of the steel sheet. The Fig.2d represents microstructure of the samples area with maximum impress deformation of ε~ 6.8%. Here, the grains located in the impress deformation region have grown through the whole thickness of the investigated steel sheet. The size of these grains is about 400 – 500 µm.

The experimental materials with impress deformation of ε~ 3,8 % and ε~ 4,5% are shown in Fig. 2b and Fig. 2c respectively. The huge grains have grown also under of applied impress deformation area. However, the grain size depends on the value of applied impress deformation. After analyses off all pictures in the Fig.2, one can to conclude, that grain size directly depends on the value of impress deformation. On the other hand all the observed huge grains grow to opposite direction of strain increasing. It means that grain boundary motion has directional character.

These facts lead one to conclusion that application of particular deformation to the samples with combination of heat treatment leads to activation of abnormal grain growth in the investigated grain oriented steels, see Fig.2.

Local misorientation map obtained from EBSD analysis performed on impress deformation area of the investigated sample before temperature annealing is presented in Fig. 3. Local misorientation map is displaying small orientation changes on the map, highlighting regions of higher deformation. Hence, the Fig.3 represents an analysis of stress (or dislocation density) distribution in the region of applied impress deformation. As one can see, there are different areas with different values of local misorientations. According to the key, see the Fig.4, higher stress has been accumulated in the surface region where the impress deformation was applied. The intensity of the generated stress decreases through the whole thickness of the sample. These confirm a fact that there is a gradient of accumulated stress through cross section of the steel sheet generated by impress deformation.

The IPF map of longitudinal cross section of the investigated steel with impress deformation after heat treatment at 900ºC for 2 min is presented in Fig.5. This IPF map was prepared from the region with deformation intensity about $\varepsilon \sim 2.2$ %. It is easy to notice from the IPF map that the fine grains have different crystallographic orientation. However, the huge growing grain has the Goss orientation. In other word it was obtained an abnormal growth of [110]{001} oriented grain that starts grow in area of applied impress deformation.

Hence, the final microstructure in the investigated GO steel mainly depends on applied deformation or in other word dislocation density of the deformed sample. It is also important to note that the grains in the investigated materials grow along the direction of the deformation gradient decrease.

4. Conclusions

The grain boundary migration induced by deformation gradient in GO steel was investigated. Different values of deformation gradient were applied to the investigated GO steel.

Summarizing the obtained results in the present work one can conclude:

1. The final microstructure of annealed materials is dependent on applied value of deformation.
2. The grain growth process proceeds along the direction of the deformation gradient decrease.
3. The description of application of deformation gradient enables to investigate the dynamic of grain growth in dependence of deformation intensity within one sample.
4. The intensity of grain boundary migration is dependent on the value of deformation gradient.
5. The primary recrystallized microstructure was observed in the samples region where no impress deformation was applied.

Acknowledgement

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