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PREPARATION OF NO SILICON STEELS WITH COLUMNAR MICROSTRUCTURE AND LOW WATT LOSSES

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In the present work, we have used an adjusted temper rolling process for development of particular textures {100}<0vw> in vacuum degassed non-oriented silicon steels. The main idea behind the improvement of soft magnetic properties relies on deformation induced grain boundary motion and heat transport phenomena through the cross-section of sheet plane promoting the preferable formation of columnar or huge grains with desired orientation. The vacuum degassed non-oriented steel with silicon content 1,3 %wt. was taken from industrial line after final annealing. The columnar microstructure with pronounced intensity of cube and Goss texture components in the investigated non-oriented steel was achieved by using deformation induced growth of ferrite grains during the continuous final annealing at dynamic conditions. This thermal treatment was carried out at the laboratory furnace with the heating rate of Vh~25ºC/s and cooling rate of Vc~7ºC/s. The electron backscatter diffraction was used to determine the crystallographic orientations of grains with respect to individual rolling planes and rolling directions. The magnetic measurements demonstrated that the watt losses of investigated steels treated by suggested approach were decreased from 9,7 W/kg to 6,5W/kg.

Keywords: silicon steel, magnetic isotropy, watt losses, texture analysis

1 INTRODUCTION

Despite of long history of continuously improved magnetic properties, the further development of non-oriented electrical steels is still an exciting field for industrial and joint fundamental research. Today, the driving forces for research and development are on one hand increasing quality demands and on the other hand the pressure to reduce manufacturing cost in order to stay competitive on the market. Non – oriented electrical steels are iron –silicon alloys with varying silicon contents which have similar magnetic properties in all directions in the plane of the sheet and belong to the important group of soft magnetic materials [1]. The directional isotropic magnetic properties can be provided by (100) [*0vw*] so called "rotating" cub texture. This fact means high permeability in the plane of sheet; hence such a texture state to be expected improves the efficiency of electrical devices. They are principally used for motors, alternators, generators, ballasts, small transformations and a variety of other electromagnetic applications. The magnetic properties of electrical steels such as magnetization curves, permeability and specific losses are, to a large extent, correlated with the microstructure and crystallographic texture [2]. High permeability and low iron loss have been particularly required in recent years in order to achieve higher efficiency and hence energy saving.

There are two classes of non-oriented (NO) electrical steels: the semi-processed (SP) and the fully-processed (FP) electrical steels. The processing of FPNO steel comprises hot rolling, cold rolling, final annealing and coating. In the case of SPNO material grades a temper rolling follows the annealing and a final annealing, mostly done for the stamped parts at the customer's site. During this annealing a deformation induced grain growth and elimination of residual stresses take place [3]. The final annealing of the SPNO (according to EN 10 126 norm) has some disadvantages from the deformation induced grain growth point of view. The main detrimental effect follows from a limitation of heating rate during annealing that leads to early recovery processes in the temper rolled NOSP steel. This in turn lowers the driving force of deformation induced grain boundary motion before the optimum temperature is achieved. Moreover, the whole process cycle: heating, annealing and cooling lasts approximately 10 hours according to EN 10 126. Before final continuous annealing, the FPNO steel passes through high intensity cold rolling reduction (more than 75%). The recrystallization process of highly deformed ferrite grains takes place during the annealing process [4]. That is why it is not possible to use the deformation induced grain boundary motion phenomena for grain growth development, in this case.

The present paper is focused on use of deformation induced grain boundary motion mechanism during dynamical continuous annealing process of SPNO steel. The aim of the work is to develop large grained microstructure with increased intensity of "Cube" {100}*<0vw>* and/or "Goss" texture components.

2 EXPERIMENTAL PROCEDURE

As experimental material, vacuum degassed NO steels was used with the chemical composition presented in Table 1. The steels were taken from industrial line after final continuous annealing.

The experimental material was treated under laboratory conditions. The steel laminations were heated up to 250°C and thereupon (during cca. 2 sec) were temper rolled within one pass at particular rolling reductions. The thickness rolling reductions were varied as follows: 2%, 4%, 6%, 8% and 10%. Subsequently, the rolled materials were annealed in pure hydrogen H_2 atmosphere upon dynamical heat treatment conditions. The annealing temperatures applied to the exper-

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imental steel were 850°C, 900°C and 950°C with holding time at given temperature 5 min.

After the annealing, the microstructure of the samples was examined on the longitudinal cross-section, using light optical microscopy. An average grain size in the chosen microstructural states was estimated by means of metallographic analysis software. On the other hand this software allows get visible all the grain boundary. Texture analysis of the investigated samples was performed by EBSD method on the longitudinal cross-section. The AC hysteresis loop measurements were made at frequency 50 Hz by using the commercial REMACOMP C-705 system from MAGNET-PHYSIK Dr. Steingroever GmbH. The watt losses of the experimental samples were measured in AC magnetic field with the frequency 50Hz and magnetic field intensity 2500A/m on the toroid with external diameter 25mm and internal diameter 15mm.

Table 1. Chemical composition of the steels, wt. %

Sample	Thickness, (mm)	C, (%)	Si, (%)	Mn, (%)	P, (%)	Cu, (%)	Al, (%)
S	0,5	0,005	2,3	0,27	0,008	0,085	0,37

3 RESULT AND DISCUSSION

In order to explore the microstructure and texture evolution of the investigated temper rolled non-oriented silicon steel in the applied temperature range, an optical microscopy and EBSD analyses were performed. Fig.1 shows the changes occurring in the microstructure of the experimental steel in dependence on annealing and temper rolling conditions. The microstructure of the steels received from industrial line after the final continuous annealing is presented in Fig. 1a. Here, the microstructure of this sample is characterized by homogenous distribution of fine grains with mean grain size approximately 35 – 40 µm. The commencement of formation of coarse grained microstructure is represented in Fig. 1(b), where the coarse growing grain is consuming the primary recrystallized grain matrix. This microstructure was obtained on the temper rolled sample with 2% deformation after 5 min annealing at 850°C. Microstructure of experimental steel after temper rolling 4% in thickness reduction and following annealing at 950°C/5 min. represent a complete coarse grains, see Fig. 1(c). In this case, the experimental steel reveals complete coarse grain growth with the maximal average grain size d =630 µm. The dependence of average grain size of experimental steel on annealing temperature and value of applied deformation is shown in Fig. 2. It is well seen that, maximum of the mean grain size was obtained in samples subjected to temper rolling with 4% reduction in thickness. As on can see the following increasing of the value of applied deformations up to 10% let to formation the microstructure development with average grain size approximately 150 – 250 µm. This is due to that at higher value of deformation (in the range from 6% to 10%) much more numbers of the primary recrystallized grains, than at less deformations, are increasing their stored energy which is necessary for process of secondary recrystallization during the heat treatments. Because of this a lot of grains begin to grow and inhibit each other during the secondary recrystallization. As a result the final microstructure of these samples is characterized by decreased of average grain size. Figure 3 shows the results obtained from the EBSD measurements which present intensities of particular crystallographic texture components in the as received state and after the application of 4% rolling deformation with subsequent annealing at 950°C during the 5 minutes. From the colored Pole figures depicted on the Fig. 3(a) that corresponds to the sample after continuous final annealing at industrial conditions one can

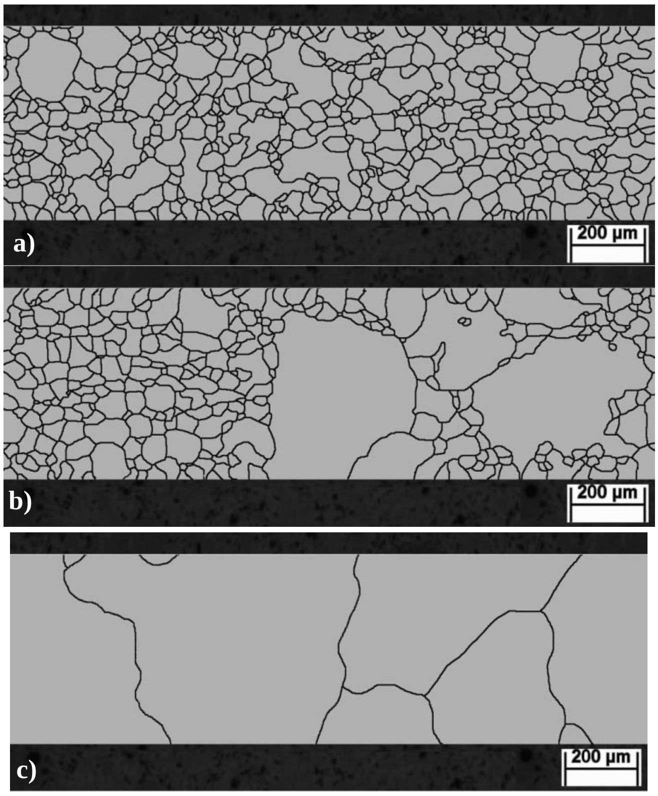

Fig. 1. The experimental material after a) final annealing in industrial conditions. The temper rolled experimental material with b) 2% and c) 4% of deformation annealed at 950°C/5min. in dynamic conditions.

see that intensity of so-called deformed texture {111}<110> is enhanced in comparison with other orientations. The desirable cube and Goss crystallographic orientation are characterized by low intensity. On the other hand, high intensity so – called rotation cube texture which was measured in the specimens annealed in the temperature range corresponding to the coarse grain growth. It is clearly visible that the enhanced rotation texture obtained in the specimen with 4% of deformation annealed at 950ºC for 5 min is very close to the ideal cub crystallographic orientation see Fig. 3b. Moreover the cube texture obtained in this specimen is more pronounced than that obtained in the laboratory annealed specimens at similar temperature but with higher values of applied deformations (6-10%), see Fig. 2. This also suggests that there is a narrow deformation region around 4% where the grain growth of coarse grains has ideal conditions for development at 950ºC for 5 min.

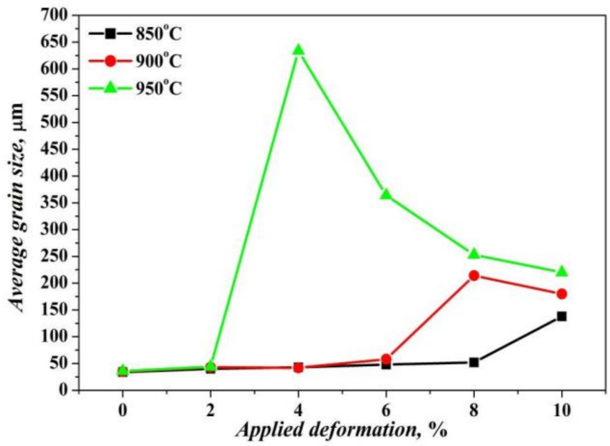

Fig. 2. Dependence of average grain size on applied deformation in temper rolled experimental steel heat treatment at three different temperatures

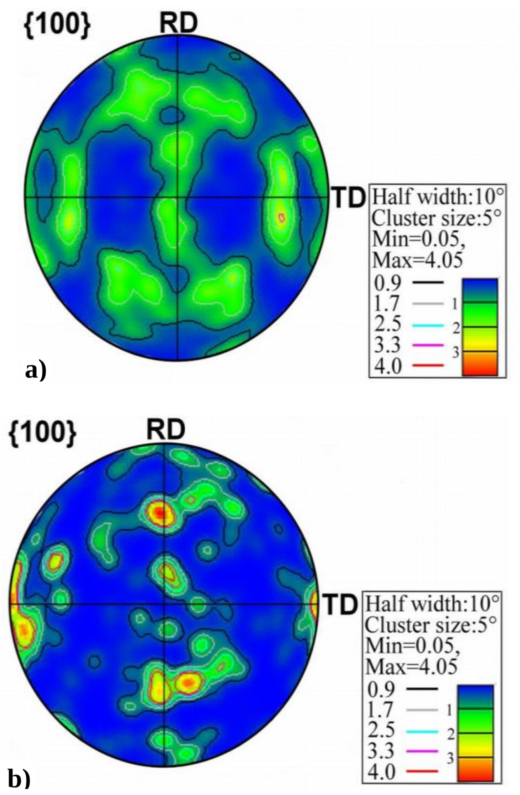

Fig. 3. The Pole figures represents the cube orientation intensity {100}<*0vw*> for sample: a) taken from industrial line and, b) after laboratory annealing

Precise estimation of the relationship between microstructure, texture and domain wall motion in the experimental NO steel can be obtained through measurements of magnetic watt losses. The Fig. 4 presents dependence of the measured AC losses on the applied deformation. The watt losses of the experimental samples were measured in AC magnetic field with the frequency 50Hz and magnetic field intensity 2500A/m on the toroid with external diameter 25mm and internal diameter 15mm. The magnetic loss of the sample taken after the industrial final continuous annealing is shown on the same graph by the filled black circle.

The performed magnetic measurements are representative and made in order to distinguish specimens after different model thermo – mechanical treatment (see Fig. 1). Additionally, the measurements clearly show the differences between magnetic properties of the specimens treated under laboratory and industrial conditions. The lowest value of the magnetic loss for the experimental steel annealed in laboratory conditions was 6,5 W/kg. It is a significant decrease of the watt loss as compared with the received state where this value was measured approximately 9,7 W/kg. The AC hysteresis loops of the laboratory annealed sample and the reference industrial NO steel sample are plotted in Fig. 5. The coercivity values were determined from the enlarged central part of the corresponding hysteresis loops. The achieved coercive field values of the laboratory treated samples are lower than reference samples taken after industrial final annealing. The coercivity value decreased from 224 A/m to 117 A/m in AC magnetic field.

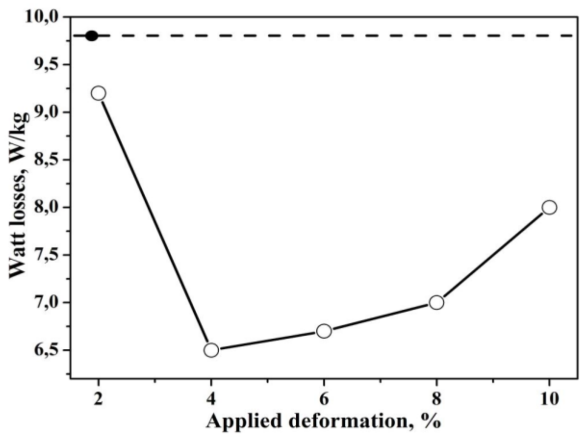

Fig. 4. Dependence of the watt losses on the applied deformation, • - the watt losses of specimen taken after the final annealing in industrial conditions.

The proposed process of microstructure and crystallographic texture formation is based on the use of deformation induced grain boundary motion during continuous annealing of steel. A driving force of the deformation induced grain boundary motion relies on the gradient of deformation energy [5]. It means that grains possessing the low energy grow at the expense of the grains with high deformation energy [6]. Application of optimal deformation conditions (with sample preheating before rolling reduction) leads to generation of deformation gradient through the cross section from the surface to the central region. This is due to the anisotropy of temperature field through the thickness of the steel sheet when the center of the material has a higher temperature than the surface region. Hence, the difference in the local value of an achieved deformation resistance can be up to 20 MPa. During the conventional rolling conditions, *ie* temper rolling, a higher deformation intensity is achieved in the central region of the sheet plane [7]. The favorable cub texture components are mainly distributed in the sub surface grains. Due to this fact the grains with such orientation will preferably grow to the middle region of the steel sheet [8].

The elaborated deformation state provides condition for the deformation induced ferrite grain growth that is directed from the surface to the central region of the sheet. Moreover, such deformation state leads to selectivity in the growth of grains with favorable rotating cub {100}<*0vw*> and Goss {110}<001> texture components. Such a microstructure and texture has a positive impact on the soft magnetic properties including a decrease of coercivity, which in turn favorably affects the watt losses.

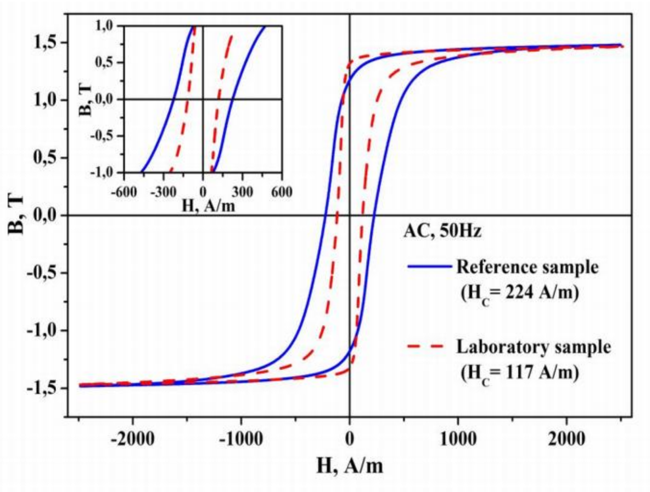

Fig. 5. AC hysteresis loops of the laboratory sample with 4% of deformation annealed at 950°C/5min. and the reference sample final annealed in industrial conditions.

4 CONCLUSIONS

We have shown that a columnar microstructure can be achieved in isotropic electrotechnical steels by using a deformation induced ferrite grain growth during the final annealing. As one can see, the laboratory thermo-mechanical treatment led to increased intensities of the favorable cube (100)[0vw] and Goss (110)[001] texture components and to a decrease of the unwanted (111)[0vw] deformation one.

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