Proceedings of the 16th Czech and Slovak Conference on Magnetism, Košice, Slovakia, June 13–17, 2016

The Effect of Cryo-Rolling and Annealing on Magnetic Properties in Non-Oriented Electrical Steel

T. Kvačkaj[a], P. Bella[b], R. Bidulský[a], R. Kočiško[a], P. Petroušek[a,*], A. Fedoriková[a], J. Bidulská[a], P. Jandačka[c], M. Lupták[a], M. Černík[d] and R. Pernis[e]

[a]Institute of Materials, Faculty of Metallurgy, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia

[b]ŽP VVC s.r.o., Kolkáreň 35, 976 81, Podbrezová, Slovakia

[c]Institute of Physics, VSB-Technical University of Ostrava, 17.listopadu 15/2172, 70833 Ostrava, Czech Republic

[d]U.S. Steel Košice, s.r.o., Research and Technology Center, Vstupný areál U.S.Steel, 044 54, Košice, Slovakia

[e]Alexander Dubček University of Trenčín, Pri Parku 19, Trenčín-Záblatie, Slovakia

The goal of the present work is to compare progressive technology — rolling at cryogenic temperature and classical rolling at ambient temperature followed by an investigation of their impact on the final microstructure and the magnetic properties of non-oriented electrical steel. Non-oriented electrical steel is characterized by high magnetic induction, low magnetic losses, and low coercivity. The best magnetic properties are achieved using preferable texture and optimal grain size. In this paper there is analyzed the percentage of different textural components after cryo-rolling and after rolling at ambient temperature. To obtain maps of inverse pole figures, the electron backscatter diffraction method was used. The main contribution of this study was that the samples rolled at cryo conditions and after final annealing reached better magnetic properties than at ambient temperature, which was reflected by low magnetic losses and coercivity.

DOI: 10.12693/APhysPolA.131.1105

PACS/topics: 75.50.Bb, 81.05.Bx, 81.40.Rs, 81.40.Ef

1. Introduction

Soft magnetic materials are easily magnetized and demagnetized. Some important parameters are the relative permeability, the coercivity, the saturation magnetization, and the electrical conductivity [1–3].

Non-oriented electrical steels are characterized by approximately the same magnetic properties in all directions of the plane of the sheet [4, 5].

Microstructural parameters such as the crystallographic texture and grain size have a strong influence on the magnetic properties of non-oriented electrical steel. With increasing grain size there are reduced hysteresis losses but the eddy current losses are increased. Therefore, the grain size is important for reducing energy losses [6]. According to the authors of Refs. [7, 8], the optimal grain size is 150 μm. The most appropriate texture for the lowest energy losses is $\{001\}$. On the contrary, the most inconvenient texture is $\{111\}$ for non-oriented electrical steel. The authors [9] have shown that an increase temperature annealing caused improving the magnetic properties of these steels, which is associated with increasing intensity of the Goss texture $\{110\}$, $\langle 001 \rangle$.

Electron backscatter diffraction (EBSD) is a microstructural-crystallographic characterisation technique to study any crystalline or polycrystalline material. The technique involves understanding the structure, crystal orientation and phase of materials in the scanning electron microscope (SEM). Typically it is used to explore microstructures, revealing texture, defects, grain morphology, and deformation [10].

The effect of plastic deformation on the properties of non-oriented electrical steels has a significant difference in rolling at cryo conditions and ambient temperature [11–14]. The progressive methods for this material are currently, like rolling at the cryo conditions, not explored.

Based on present knowledge of non-oriented electrical steels are high demands on the magnetic properties such as low magnetic losses, low coercivity, and high magnetic induction. Magnetic properties are dependent on microstructure and texture that are evolved during thermomechanical processing.

2. Experimental procedures

A chemical composition of the non-oriented electrical steel is given in the following Table I.

TABLE I

The local chemical analysis [mass %]

C	Si	Mn	P	S	Cu	Al	Fe – bal.
0.015	2.3	0.250	0.018	0.004	0.016	0.464	96.93

Rolling at the ambient temperature was realized on the rolling mill DUO 210 at the speed of movement rolls 0.66 m/s. The thickness of the samples before rolling was 2 mm and 1.3 mm after rolling. The samples rolled at cryo conditions were immersed in liquid nitrogen for 30 min.

*corresponding author; e-mail: patrik.petrousek@tuke.sk

After rolling, the samples were annealed in an electric arc furnace at 900 °C for 40 min.

The textural and crystallographic analysis in the study of the material were converted by EBSD methods in cross-section of the sheet. EBSD scans were performed on the RD-ND. The obtained EBSD data were analyzed and displayed in the program Orientation Imaging Microscopy OIM 4.6. The crystallographic orientations of individual grains were determined by inverse pole figures (IPF) maps. The aim was to obtain dependence for the deformation process in the respective grains from their crystallographic orientation in the plane of the sheet thickness.

Measuring of the magnetic properties was carried out on the device SST. This device uses a measuring system Remacomp C200. Basic dimensions of the samples for measurement were $l = 280$ mm, $b = 30$ mm and $h = 1.3$ mm. The samples were taken in the direction of rolling. The measurements were made at a frequency of $f = 50$ Hz, $B_{max} = 1.5$ T.

3. Results and discussion

In Fig. 1 there is shown a comparison of hysteresis loops and permeability for two types of samples ($f = 50$ Hz). The first type of samples is after the cryo-rolling and the second type of samples are after the rolling at the ambient temperature. After cryo-rolling there was increased the proportion of deformation twins. From the plot, it is seen that the samples rolled at the ambient temperature have better magnetic properties as the samples rolled at the cryo conditions.

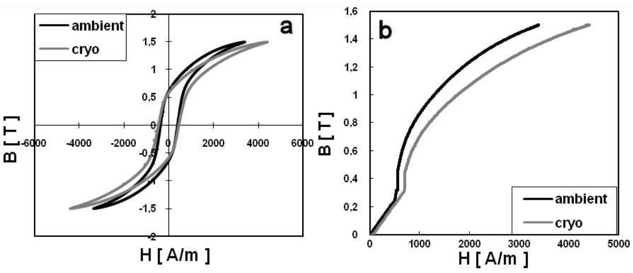

Fig. 1. The comparison of the hysteresis loop (a) and permeabilities b after cryo-rolling and after rolling at ambient temperature.

TABLE II

Coercivity for samples rolled at ambient and cryo conditions and after annealing.

	Ambient	$T_{an} = 900\,°C$
cryo H_c	452 A/m	266 A/m
ambient H_c	380 A/m	289 A/m

Coercivity is shown in Table II. The table values of coercivity for the samples rolled at ambient and cryo conditions for annealed and non-annealed samples. It follows that after the annealing, the coercivity markedly decreases namely for cryo-rolled samples about 41.2% and at ambient rolled about 23.9%.

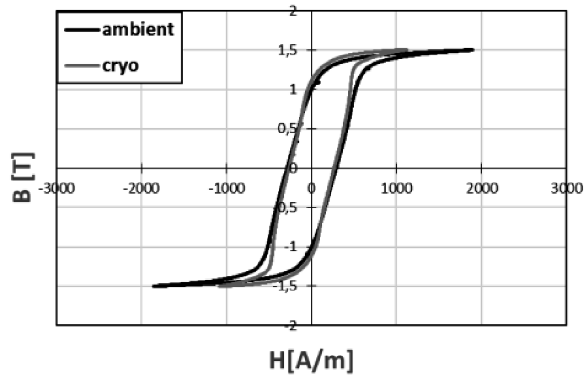

Fig. 2. A comparison of samples rolled at ambient and cryo conditions after annealing at a temperature $T = 900\,°C$ by hysteresis loops.

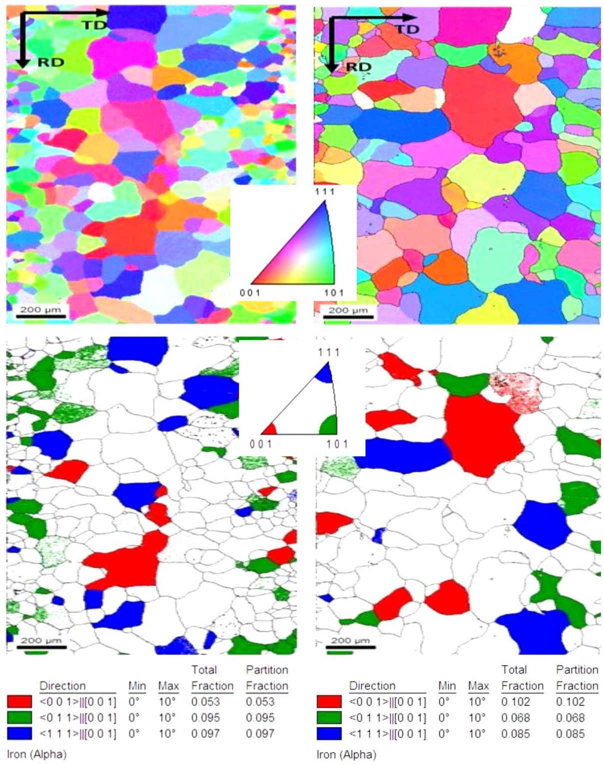

Fig. 3. Maps of inverse pole figures for samples rolled at the ambient (left-side) and cryo conditions (right side).

Figure 2 shows a comparison of hysteresis loops after annealing at 900 °C. Magnetic losses on the samples rolled at ambient conditions were $P = 10.36$ W/kg and at cryo conditions $P = 10.13$ W/kg.

Figure 3 shows the IPF maps of annealed samples. The samples were rolled at ambient temperature and the cryo

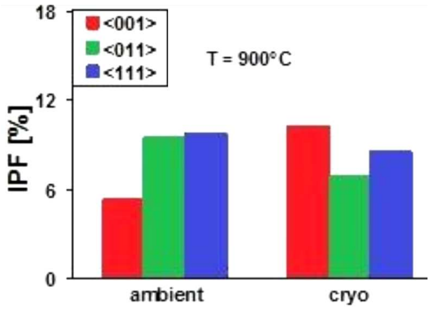

Fig. 4. Comparison of textural components during rolling at cryo conditions and rolling at ambient temperature.

conditions. In the samples rolled at cryo conditions cubic texture is developed almost twice more than in the samples rolled at the ambient temperature. In the samples rolled at ambient temperature grains mostly have the Goss orientation {110}⟨001⟩ and also grains with planar orientation {111}.

For samples rolled at cryo conditions there was achieved a higher percentage of the cubic components {001} and Goss components (Fig. 4), which are the best in terms of magnetic properties, as it has got the lightest (shortest) magnetization direction ⟨100⟩. It is also achieved by a lower amount of textural components {111}, which define the most difficult magnetization direction.

The results showed that the application of cryo conditions combined with annealing shows greatly improved magnetic properties compared to conventional technologies of processing non-oriented electrical steel. For the following reasons — the area of the hysteresis loop is smaller; it means that the samples exhibit a reduced loss of magnetization alternating current and lower coercivity. Another reason was in the high proportion of deformation twins. These deformation twins prevent the transition of magnetic domains and other grid defects in the material that are caused by cryo-rolling.

4. Conclusions

In the present study there are compared the magnetic properties of steels rolled in laboratory rolling conditions, at cryo and ambient temperatures.

According to this study, the following conclusions can be made:

- the samples rolled at cryo conditions achieve better magnetic properties after annealing due to optimal grain size and the increase of the cubic texture,
- after cryo rolling and annealing about 10% higher percentage of the cubic components {001}and Goss components was achieved.

Acknowledgments

This work was realized within the frame of the project "Technological preparation of electrotechnical steels with high permeability for electrodrives with higher efficiency" which is supported by the Operational Program "Research and Development" ITMS 26220220037, financed through European Regional Development Fund and supported by the VEGA project 1/0325/14. Magnetic measurements were performed in project IT4 Innovations Centre of Excellence, regulation No. CZ.1.05/1.1.00/02.0070.

References

[1] R. Bidulský, M.A. Grande, L. Ferraris, P. Ferraris, J. Bidulská, *Acta Phys. Pol. A* **118**, 802 (2010).

[2] R. Bidulský, J. Bidulská, M.A. Grande, L. Ferraris, *Acta Metall. Slov.* **20**, 271 (2014).

[3] T. Kvačkaj, J. Bidulská, R. Biduslký, A. Kováčová, R. Kočiško, P. Bella, M. Lupták, J. Bacsó, *Acta Phys. Pol. A* **126**, 184 (2014).

[4] R.Z. Valiev, I.V. Alexandrov, Y.T. Zhu, T.C. Lowe, *J. Mater. Res.* **17**, 5 (2002).

[5] Y.M. Wang, M.W. Chen, F. Zhou, E. Ma, *Nature* **419**, 912 (2002).

[6] J. Salinas-Beltrán, A. Salinas-Rodríguez, E. Gutiérrez-Castañeda, R. Deaquino Lara, *J. Magn. Magn. Mater.* **406**, 159 (2016).

[7] K. Matsumura, B. Fukunda, *IEEE Trans. Magn.* **20**, 1533 (1984).

[8] E.T. Stephenson, A.R. Marder, *IEEE Trans. Magn.* **22**, 101 (1986).

[9] F. Kováč, M. Dzubinský, Y. Sidor, *J. Magn. Magn. Mater.* **269**, 333 (2004).

[10] S.K. Chen, Q.Y. Li, Z. Miao, F. Xu, *Rare Metal Mater. Eng.* **35**, 500 (2006).

[11] T. Kvačkaj, R. Kočiško, R. Bidulský, J. Bidulská, P. Bella, M. Lupták, A. Kováčová, J. Bacsó, *Mater. Sci. Forum* **782**, 379 (2014).

[12] T. Kvačkaj, J. Bidulská, *Adv. Mater. Res.* **842**, 783 (2014).

[13] T. Kvačkaj, J. Bacsó, J. Bidulská, M. Lupták, I. Pokorný, M. Kvačkaj, M. Vlado, *Acta Metall. Slov.* **16**, 268 (2010).

[14] T. Kvačkaj, *Metalurgija* **39**, 185 (2000).