Monitoring Magnetic Anisotropy Variations in Cold-Rolled Steels by Magnetic Barkhausen Noise Method

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Abstract

Texture formation in the cold rolled low-C steels is very important for subsequent metal forming operations and service performance. The aim of this study is to nondestructively monitor the variation of magnetic anisotropy, which is influenced by crystallographic texture, in cold rolled steel sheets by magnetic Barkhausen noise method. Barkhausen noise emissions of a series of sheets were measured with 10° steps between 0°-360°. Microstructure of the material was analyzed, hardness values were measured, and XRD texture maps were obtained. These results were compared with the results of microstructure investigations and XRD texture analyses.

Keywords: Steel, Cold Rolling, Magnetic Anisotropy, Texture, Magnetic Barkhausen Noise

1. Introduction

Cold-rolling of mild steels causes texture in which certain crystallographic planes tend to orient themselves in a preferred manner with respect to the direction of maximum strain. Before starting any subsequent manufacturing step, knowing the state of texture is vital. Texture is generated by hot/cold rolling and recrystallization during production of sheets. Plastic anisotropy is related with the microstructure such as grain size and dislocation structure, whereas elastic anisotropy is affected by crystal texture. Conventional methods, giving limited information that is gained from representative samples such as calculation of $r$ and ∆$r$ by mechanical tests, metallographic investigation, and x-ray diffraction are either destructive or time consuming.

Determination of certain magnetic properties seems to be useful for analyzing the anisotropy of the ferromagnetic steel sheets since microstructure affects the mobility of magnetic domain walls. Magnetic Barkhausen Noise (MBN) method might be a challenging alternative to the existing methods. Ferromagnetic materials consist of micro- magnetic regions called as domain which is magnetized along a certain crystallographic direction of easy magnetization. Domains are separated from one another by domain walls. When a variable external magnetic field is applied to a ferromagnetic material, irreversible jumps of domain walls occur due to discontinuous domain wall motion, nucleation and annihilation of domains. When the strength of externally applied magnetic field reaches a critical level, motion of the domain wall continues by Barkhausen jumps which can be detected as the voltage pulses induced in a pick-up coil positioned close to the surface. The signal is amplified, filtered, processed and obtained time domain and amplitude-frequency spectrum of MBN signal. Residual stress state and microstructural features such as inclusions, grain boundaries affect the magnetic domain wall motion. Residual stresses influence the area of the 180° and 90° domain walls (Figure 1) whereas microstructure affects the pinning sites for domain walls. It has been proposed that main motion capability of the domains coming from 180°. In textured ferromagnetic steels when the magnetically soft crystallographic direction [111] of the grains is parallel to the magnetization direction, 90° and 180° domain wall motions occur; however, if [111] direction is parallel to the magnetization direction only 180° domain walls move and rotate. Therefore, texture condition directly affects the MBN emission.
Anisotropy of magnetic property is affected by residual stress, crystallographic orientation and microstructural properties. MBN signals increase under tensile stress and decreases under compressive stress [1-3]. This behavior is associated with an increase in the 180° domain wall population in the direction of applied tensile strain and field, and a decrease under the compressive strain that is sampled by the applied field direction. Cold rolled low-C steels show a strong RD//<110> fiber texture with a {112} <110> maximum peak position and ND//<111> fiber texture with a {111} <110> peak position [4]. {112} <110> and {111} <110> texture components become strong in the greater than 70% cold rolled sheets, and the {111} <112> texture component becomes strong in the fully recrystallized sheets [4,5]. In individual iron grain, domain magnetization vectors tend to lie along <100> direction [6] which causes increase in MBN signal formation, and no <100> texture parallel to the rolling direction forms because of the transverse formation of easy magnetization axis. Since the total grain boundary area in the transverse direction increases due to grain elongation, there are more obstacles to domain motion, which results in a higher MBN emission [7,8]. Crystallographic texture development is one of the reasons magnetic anisotropy changes. However, there is significant scatter about the ideal texture until 80-90% deformation is reached when texture formation is complete. Macro (overall sample) and micro (at grain boundaries or between crystallographic planes) residual stresses bring their own contribution to the magnetic anisotropy of the cold rolled samples [9]. It was reported that MBN rms voltage in the cold-rolled mild steels increases with reduction ratio below 20%, and tend to saturate at higher rolling ratios; MBN energy and MBN rms voltage show the same tendency with increasing rolling percentage [10]. MBN pulse height distribution correlated well with the variations in the magnetic anisotropy of the nuclear reactor pressure vessel steel samples, as the preexisting anisotropy direction was destroyed at 25% reduction ratio, increasing again and aligning with the rolling direction while deformation progressed to 60% reduction [11]. This study aims to contribute to the applicability and efficiency of MBN method for magnetic anisotropy and texture analysis in cold-rolled ferromagnetic steel sheets.

2. Material and Methods

Analyses were performed on the commercial ferritic steel sheets having the same chemical composition (Table 1), but with different cold-roll reduction ratios of 48% ($\Delta r=0.27$; $r=1.27$), 73%, and 82% ($\Delta r=0.17$; $r=1.73$). A second sample series were prepared by stress relieving the as-received sheets at 500°C/1h; and finally one reference sample was prepared by normalization heat treatment (austenitization at 850°C for 1h, then air cooling).

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<th>Table 1. Chemical composition of the ASTM 1006 steel (%)</th>
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<td>C  Si  Mn  S  Cr  Mo  Ni  Al  Co  Cu  Ti</td>
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<tr>
<td>0.02 0.003 0.14 0.004 0.02 0.004 0.015 0.04 0.004 0.025 0.001</td>
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Barkhausen noise measurements were performed using “Rollscan 500-2” and S1-138-13-01 probe with 10 dB amplification. The excitation frequency was 125 Hz and received signals were filtered in the range of 1-200 kHz. MBN sensor were put on a point on the surface of the sample and rotated in the radial direction with fix degree increments of 10° until it completes 360°. Next, the MBN polar graph so called Directional Diagram was drawn.

Seifert XRD 3003 PTS system was used to determine the state of texture in the samples. A 2 mm collimator was used in order to include high number of grains in texture measurement. In each sample (100) and (111) plane texture measurement were made to obtain raw pole figure data. The samples with 60x60 mm dimensions were electro-polished down to 100 µm aiming to equalize grinding effect and aiming to catch the depth in Barkhausen noise measurements.

3. Results and Discussion

3.1. Microstructural Investigation

The optical micrographs and hardness values of some samples are given in Figure 2. The microstructures of all samples consist of ferrite, and no other phases that might affect the MBN activity exist.

(100) and (111) pole figures obtained by XRD measurements are given in Figure 3. (100) is the easy axis of magnetization for bcc metals. For 48% reduction (100) intensity in the rolling direction is higher than that in the transverse direction. However, as the amount of thickness reduction increases the condition is reversed which is the indication of an increase in (100) texture in the rolling direction.

The Directional Diagrams (polar MBN graphs) are given in Figure 4 and Figure 5. Although an inverse proportion between grain size and Barkhausen emission was reported [12, 13], the effect of cold rolling is not only over grain size; an alignment is also provided in cell structure that causes an increase in dislocation density and in the amount of dislocation tangle. Grains elongate in the rolling direction and correspondingly, total grain boundary area is higher in the transverse direction which may cause higher Barkhausen emission. In addition, since the increase in the amount of dislocation tangle cause an extra nucleation and pining effect in the transverse direction, it has a positive effect in the MBN emission until a critical cold deformation percentage. Directional Diagrams show that thickness reduction at about 70% hinders domain wall motion and decreases MBN emission in the transverse direction due to excessive number of dislocations.

Changing direction of the magnetic easy axis becomes possible to prove via these results. While peak heights in lower reduction values are higher in transverse direction, in the following cold deformation amounts, this difference moves towards rolling direction because of magneto-crystalline effect.

Stress relief process minimizes the residual stress and decreases dislocation density. Average MBN emission shows a significant decline in comparison with the cold rolled samples. The reason of this decline seems to be domain nucleation and the decrease in the amount of dislocation tangle which serves as pinning site.
48% reduction, 92 HV0.5

82% reduction, 98 HV0.5

**Figure 2.** Representative micrographs (top and side views) of the as-received samples

**Figure 3.** XRD pole figures of the as-received samples (%48 and %82)
Figure 4. MBN Directional Diagrams (polar graphs) of the samples

Figure 5. Comparison of the MBN Directional Diagrams of the samples
If XRD measurements are linked with magnetic easy axis formation, it is seen that (100) orientation have a significant impact. In terms of evaluating (100) intensity variation; it can be observed that intensity of the 48% deformed sample is more profound in the transverse direction, the sample exhibits a highly anisotropic behavior. In the higher thickness reductions, there is an increase in the intensity of (100) in the rolling direction. Combined with the microstructure and higher dislocation density, domain wall motion hinders and depending on these effects, magnetic easy axis shifts from transverse to rolling direction.

MBN signal versus applied field strength graphs (MBN fingerprint) of the samples in the rolling direction, obtained by µScan module, are given in Figure 6. The peak heights of MBN fingerprints increase with increasing % cold work. The reason seems to be the severity of cold deformation and reduced grain size depending upon which cell formation also increases and mean free paths of 180° walls shortens [14]. Moreover, since cold rolling makes the materials harder, a higher magnetic field is required to reach magnetic saturation. For this reason, in lower thickness reductions, peak value shifts to the left. The representative hysteresis curves that were determined by local MBN measurements in the rolling direction are presented in Figure 7. As the % deformation increases the magnetic field necessary for magnetic saturation, retentivity (B) and coercivity (H) increase. The higher the coercivity the stronger is the hinderance of domain wall movements during magnetization.

Figure 6. MBN fingerprints of the as-received sheets (in the rolling direction)

Figure 7. Representative hysteresis curves of the as-received samples (in the rolling direction)
4. Conclusions

The applicability of Magnetic Barkhausen noise (MBN) method for determination of magnetic anisotropy and texture in the cold-rolled ferritic steel sheets were investigated. MBN polar graphs showed a significant variation in magnetic anisotropy as a function of the degree of cold-rolling. Similar tendency was observed in the crystallographic texture obtained from XRD analyses. The competing effects of crystallographic texture, microstructure and macro/micro residual stresses create complex magnetic anisotropy in the cold-rolled and recrystallized steels. Further investigations are necessary to differentiate the individual effects of the competing parameters on MBN emission.

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References