Non-Destructive Characterization of Cold Rolled Low-Carbon Steels

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Abstract
Cold rolled steels are widely used as basic materials in wide range of end applications such as automobiles, electrical appliances, and various types of containers. Plastic deformation affects the magnetic properties due to magnetic-elastic interactions between the magnetic domain walls and dislocations and residual stress fields. The aim of this study was to investigate the ability of the Magnetic Barkhausen Noise (MBN) method for non-destructive evaluation of the cold-rolled low-C steels. The results showed that the MBN emission is sensitive to the severity of cold rolling however the measurement method needs improvement to differentiate the effects of microstructure and residual stress.

Keywords: cold rolling; low-C steel; non-destructive evaluation; magnetic Barkhausen noise

1. Introduction

Dimensional accuracy, deformability and service performance of the cold-rolled low-C steel products are mainly dependent on the residual stresses and texture. Macro residual stresses cause distortions during subsequent production stages whereas deformability of the sheets are critically dependent on the texture. The most significant factor for cold rolling texture in low-C steels is the degree of rolling reduction, and to some extent the prior texture.

Ferromagnetic materials tend to minimize their internal magnetic energy by forming a multi-domain structure in which the domains have randomly distributed magnetization directions (Figure 1). Within a domain, whose size is less than the grain size, all magnetic moments are aligned and the electron spins have the same orientation. The interactions among the magnetic moments of the atoms cause a minimum energy condition when magnetic moments have a parallel alignment causing a directional anisotropy. The spontaneous tendency of the magnetic moments to rotate into the magnetically easy directions is a critical factor for magnetic properties. Plastic deformation affects the magnetic structure of the ferromagnetic materials. Crystallographic anisotropy and stress anisotropy determine the directions of the magnetically easy axes. Thus, the combined effects of crystallographic texture and residual stresses create complex magnetic anisotropy in the cold-rolled steels.

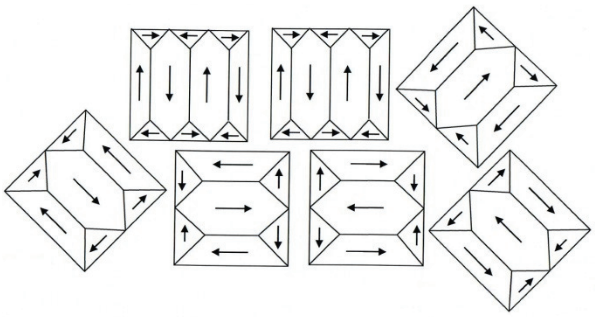

Figure 1 Schematic view of magnetic domains and domain walls

Magnetic Barkhausen Noise (MBN) is affected by metallurgical structure, residual stress and material anisotropy. Under the effect of an external magnetic field when a domain wall is moving it has to pass the discontinuities or obstacles (dislocations, grain boundaries, precipitates, etc.) in the crystal structure. A local variation in the easy axis, which lowers the energy of the domain wall interacting with the obstacle, occurs depending upon the type of obstacle. Also, strain fields in the lattice create additional magnetic anisotropies in the microstructure. A stronger magnetic field is needed to prevent the domain wall from being pinned at the obstacles. Thus, investigation of domain wall pinning can give information about the microstructure such as presence of dislocations, grain boundaries, second phase grains or precipitates. For instance, the domain walls face very strong barriers such as dense dislocation tangles and cell structures created by dislocations whose density in metals typically varies in the range 10^{10}-10^{16} m^{-2} [1].

MBN technique can detect the residual stress differences on the basis of the changing area in the domain walls. Compressive residual stress reduces the MBN emission due to decrease in the total area of domain walls in contrast to the tensile residual stress. Altpeter and Dobmann developed an approach combining MBN amplitude, coercivity force, distortion factor of the tangential magnetic field and dynamic magnetostriction to separate the influence of residual stress from the influence of texture [2]. Grum et al. reported that the micromagnetic method with constant magnetisation current is more reliable to analyze the degree of cold deformation [3]. Stefanita et al. measured magnetic anisotropy of cold rolled low-C steels. Angular preference of MBN energy in the undeformed sheets was destroyed at intermediate reduction ratios, and restored with further reduction [4]. Liu et al. reported that MBN r.m.s. voltage increases with reduction ratio below 20%, and tend to saturate at higher rolling ratios in the cold-rolled mild steels [5]. Bükki-Deme et al. investigated orientation and depth dependence of MBN in the rolled steel sheets. The specimens in the rolling direction showed larger MBN energy and strong depth dependence [6]. Akcaoglu and Gür reported that the MBN polar graphs show a significant variation in magnetic anisotropy as a function of the degree of cold-rolling [7]. Fiorillo et al. focused on the plastic-deformation-dependent magnetic properties of steels [9]. This study aims to investigate the ability of the MBN method for non-destructive evaluation of the cold-rolled low-C steels.

2. Experimental Procedure

Various specimens were prepared by cold rolling of annealed SAE 1015 sheets. The initial dimensions were 300mmx40mm with different thicknesses, however, the final thickness of all specimens is 3.5 mm. The specimens whose thicknesses were reduced by 20%, 40% and 60%, were characterized by metallographic investigations and hardness measurements. MBN measurements were performed on the surfaces of the specimens using Rollscan 500-2 system. The signal amplification was 10 dB, the excitation frequency was 125 Hz. The received signals were filtered in the range of 1-200 kHz. The surface residual stresses were measured by the XRD method with Cr-Kα radiation for the (211) plane. The procedure consists of posing the specimens at 0^o, 45^o, and 90^o. The stresses were calculated using the Dölle-Hauk method.

3. Results and Discussion

All specimens have ferritic microstructure, and a grain alignment exists along the rolling direction. Hardness increases with the severity of the cold-rolling.

XRD measurement results in Figure 2 show that surface residual stress in the rolling direction is slightly tensile for 20% deformation, however, it becomes compressive for 40% deformation, and reaches a maximum after 60% deformation. It indicates that the crystallographic texture effects the residual stress distribution depending upon the level of cold rolling, i.e., residual stresses are redistributed through reorientation of crystallographic planes.

Figure 3 shows that along the rolling direction the MBN signal height increases for the 20% thickness reduction, however, starts to decrease with further increase in the level of cold deformation. Similar tendency was reported in the literature [4,5]. The MBN signal height has the maximum value for the 20% deformation case where the surface residual stress is tensile. It is known that the tensile residual stress causes an increase in the MBN signal height opposite to the effect of the compressive residual stress. Thus, the changes in the MBN peak height can be attributed to the alterations in the residual stress state.

During cold-rolling, plastic deformation occurs by the motion of existing dislocations and the generation of new ones. In ferritic steel, dislocations move and dislocation sources are activated on the most densely packed planes at the beginning of plastic straining. As the severity of plastic deformation increases, new slip planes are activated and the dislocations start to pin each other which makes the plastic deformation more difficult.

Domain walls interact with dislocations to a different extent. Besides the localized interaction of domain walls with dislocations, the plastic straining interferes with the domain structure through the residual stress field. Thus, the specimens that were cold-rolled with different severity levels show differences in the Barkhausen noise emission during MBN measurements.

Cold-rolling generates a macro residual stress field across the thickness. The surface layer has compressive residual stresses, thus, it shows magnetically harder behaviour. The local compressive residual stress fields at grain size scale act as obstacles against the motion of domains.

Crystallographic texture also influences the magnetic structure and the residual stress fields, and thus MBN emission.

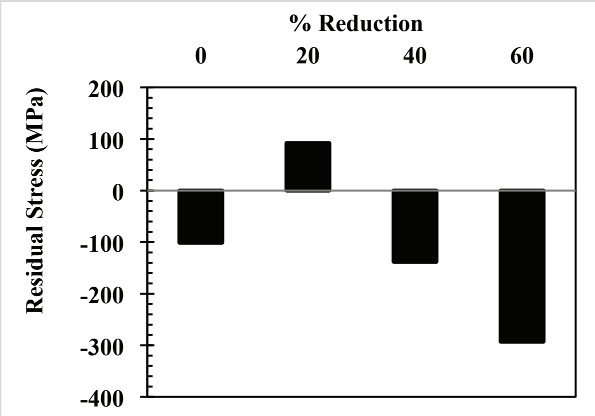

Figure 2. Effect of the thickness reduction on the surface residual stress

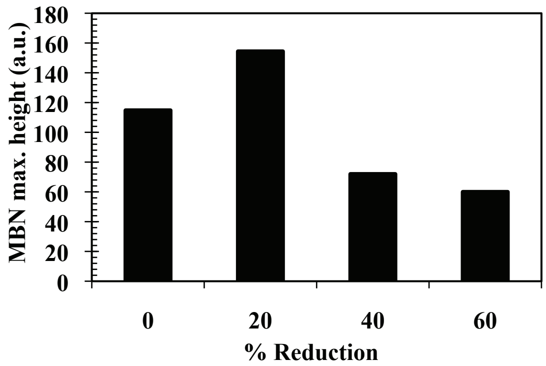

Figure 3. Effect of cold-rolling on the MBN signal height

4. Conclusion

Plastic deformation affects the magnetic properties therefore measurement of magnetic properties may provide useful information for evaluation of the cold-rolled products. In this study, the ability of the Magnetic Barkhausen Noise (MBN) method for non-destructive evaluation of the cold-rolled low-C steels was investigated.

The MBN emission is sensitive to the severity of cold rolling. The combined effects of crystallographic texture, microstructure and residual stresses create complex magnetic anisotropy.

For more efficient use of the MBN method, it is important to select the optimum magnetizing parameters and sensor. Moreover, it is necessary to separate the individual effects of the competing parameters on the MBN emission.

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