Correlation of magnetic properties with deformation in electrical steels

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Abstract. This paper investigates the utilization of magnetic Barkhausen Noise (MBN) and hysteresis loops methods for the non-destructive characterization of deformed electrical steel samples. For this reason electrical steel samples were subjected to uniaxial tensile tests on elastic and plastic region of deformations. Both the MBN and hysteresis loops were measured. The results shown a strong degradation of the magnetic properties on plastically strains. This was attributed to the irreversible movement of the magnetic domain walls, due to the presence of high dislocation density. The resulting magnetic properties were further evaluated by examining the microstructure of the deformed samples by using scanning electron microscopy.

1. Introduction
Non-destructive testing (NDT) are techniques, which are used either in laboratory or in industry, in order to evaluate the properties of a material, without causing any damage. Common NDT methods include eddy currents, magnetic particles, magnetic leakage (MDL), hysteresis loops (B – H loops), magnetic permeability (μ – H loops), magnetoacoustic (MAE), Barkhausen noise (MBN) [1-9].

It is well known that the magnetic non-destructive methods are influenced by the microstructural features of the examined ferromagnetic materials [10-23]. It has been also verified that, when a ferromagnetic material is subjected to uniaxial tensile or compressive tests, it undergoes a reconfiguration of its structure [24-27]. Thus, the deformation influence the final microstructure of the material, resulting in variations of the output magnetic signals.

The effect of the elastic and plastic deformation on the magnetic properties of electrical steels has been investigated in this paper. The utilization of both the MBN and hysteresis loops method for the non-destructive evaluation of the deformed samples. The resulting magnetic properties were further evaluated by examining the samples’ microstructure by using scanning electron microscopy.

2. Experimental procedure
The studied alloy was Non-Oriented Electrical Steel samples. Their chemical composition, as given by the manufacturer, is given in Table 1.

Table 1. Chemical composition, in %wt, of the as-received NOES.

|   | Si  | Mn  | Al  | P   | S   | C   | Fe  |
|---|-----|-----|-----|-----|-----|-----|-----|
|   | 2.18| 0.12| 0.35| 0.0009 | 0.0009 | 0.0018 | Balanced |

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Dog-boned samples were cut from the as-received samples, according to the ASTM E8 Standard. These samples were subjected to uniaxial tensile strain at preselected deformation steps. The elastic region was divided into 6 deformation states, while the plastic one into 20 deformation states. As can be clearly seen in the stress – strain curve of the examined NOES (figure 1), the sample undergoes the Lüders band propagation. For this reason, 2 strain values were defined around the yield point.

![Stress strain curve of the NOES.](image)

During the tensile tests both the magnetic Barkhausen noise and the magnetic permeability were recorded. The magnetic BN sensor consisted of an excitation coil, which was wound around the long axis of a U-shaped electromagnet. A triangular signal of 10 Hz was applied on this coil. The output signal was received by a sensing coil, which was wound around a ferrite core and placed at the centre of the electromagnet’s leg. The receiving signal was further amplified and send, via a acquisition card, to a computer, for further analysis. The rms value of the output signal was the recorded magnetic Barkhausen parameter.

The permeability magnetic sensor consisted of a double U- shape electromagnet. In this apparatus the receiving coil was wound around the examined sample. The output voltage was proportional to the magnetic permeability of the examined sample.

3. Results
Both the MBN (figure 2) and the magnetic permeability (figure 3) values were increased in the elastic deformation region. During the uniaxial tensile test, the initial easy magnetization axis rotated, in order to become parallel to the direction of the applied stress, resulting in the increment of the 180° domain walls. Thus, the tensile stresses increase the magnetic responses [28-29].

However, in the plastic deformation region it is evident a strong decrease of the magnetic permeability. Additionally, the magnetic Barkhausen rms values were also diminished. Thus, the demarcation between elastic and plastic region was evidenced by the drop of both magnetic output signals.

When the stress passes the yield strength, plastic deformation will start to occur inside the grains of the polycrystalline material. As a result, a dramatic increment of the dislocation density occurred, at the beginning of the plastic region. After the slip system reaches the required critical resolved shear stress value, the dislocation start to slip. Thus, the formation and movement of dislocations will play a crucial role in absorbing the plastic deformation. Moreover, the high density of dislocations formed as tangles for higher plastic strain rates. These tangles acted as strong pinning sites during the magnetization procedure and led to a slight but progressive deterioration of the magnetic behaviour.
Figure 2. Variation of the rms values of the MBN during the uniaxial tensile test.

Figure 3. Variations of the magnetic permeability during the uniaxial tensile test.

Microstructural studies revealed that electrical steel consisted of polygonal and equiaxed ferrite grains in the elastic region (figure 4). In the plastic region, the ferrite grains were elongated along the direction of the applied tensile stress (figure 5). The high dislocation density and the increment in the gain boundary area are pinning sites of higher energy, resulting in the pronounced reduction of both the MBN and permeability responses.

Figure 4. SEM micrograph of NOES in elastic region.  
Figure 5. SEM micrograph of NOES in plastic region.
4. Conclusions

Generally, the results attest the strong dependence between the magnetic properties and the deformation behaviour of the examined Non-Oriented Electrical Steels. The demarcation between elastic and plastic region was evidenced by the drop of both magnetic output signals. Both the MBN (figure 2) and the magnetic permeability (figure 3) values were increased in the elastic deformation region. However, in the plastic deformation the formation and movement of dislocations play a crucial role, because the high dislocation density and the development of tangles deteriorated the magnetic properties. Further studies are in progress directed mainly to the examination of the samples in TEM and a more precise investigation of the magnetic response variations between the elastic and the plastic region.

5. References

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