Correlating elastic and plastic deformation with magnetic permeability values

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Abstract. This paper investigates the utilization of magnetic permeability method in determining elastic and plastic deformation state of ferromagnetic steels. The results have shown a strong degradation of the magnetic values on plastically region due to the irreversible movements of the magnetic domain walls.

1. Introduction
Destructive testing (DT) includes methods where a material is broken down in order to determine its mechanical properties, such as strength, toughness and hardness. for this reason laboratories or industries focus on Non-destructive testing (NDT) techniques, 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, M – 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]. A high-precision magnetic sensor was used to measure slight changes in the magnetic field strength. Thus, the deformation influence the final microstructure of the material, resulting in variations of the output magnetic signals.

In this paper, the effect of the elastic and plastic deformation on the magnetic properties of electrical steels has been investigated. The magnetic properties of non-grain-oriented (NGO) electrical steels are highly susceptible to mechanical stresses. It is known that during the tensile loading of a polycrystalline material, each grain experiences a different strain depending on its orientation and constraints inflicted by its neighboring grains [28-33]. The utilization of magnetic permeability method has verified such behavior. The resulting magnetic properties were further evaluated by examining the samples’ microstructure by using scanning electron microscopy[34]. Microstructural features can influence these domain processes to modify the energy balance and ease of domain realignment and hence affect the magnetic properties of ferromagnetic materials. More details on the domain theory and the effects of the microstructure in ferromagnetic materials on their magnetic domains and properties can be found elsewhere.

2. Experimental procedure

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The studied alloy was Non-Oriented Electrical Steel samples. The 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 |

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. Two strain values were defined around the yield point.

The magnetic permeability during the tensile tests were recorded. 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**

The optimization of NGO when the application includes applications rotating electrical machines, requires comprehensive considerations of spatial variations of magnetic properties in the sheet plane and careful awareness of occurring anisotropic effects. The magnetic permeability values were increased in the elastic deformation region (Fig. 1). 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. Thus, the demarcation between elastic and plastic region was evidenced by the drop of both magnetic output signals. Within the elastic region, mechanical stresses up to yield strength cause homogeneous elongation across the entire specimen by deviating atoms of the crystal lattice from their equilibrium position.

![Figure 1. Variations of the magnetic permeability during the uniaxial tensile test.](image)
As soon as the stress passes the yield strength, plastic deformation will start to occur inside the grains. In the polycrystalline material occurred an increment of the dislocation density, at the beginning of the plastic region[30-32]. After the slip system reaches the required critical resolved shear stress value, the dislocation start to slip[33]. 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. The magnetocrystalline anisotropy, its change as well as the effect of dislocation interactions and internal stresses are directly linked to the structure of the material and thus, primarily affect the hysteresis term of the losses, which can be affirmed from the results. The excess loss term is nearly not evident in the observed cases.

Study on microstructure revealed that electrical steel consisted of polygonal and equiaxed ferrite grains in the elastic region (Fig. 2). In the plastic region, the ferrite grains were elongated along the direction of the applied tensile stress (Fig. 3). The high dislocation density and the increment in the grain boundary area are pinning sites of higher energy, resulting in the pronounced reduction of the permeability responses.

4. Conclusions

Broadly, the examined samples of Non-Oriented Electrical Steels results verify the strong dependence between the magnetic properties and the elastic and plastic deformation behaviour, due to the variations of the output magnetic signal. Yet in the plastic deformation the formation and movement of dislocations are crucial, because the high dislocation density and the development of tangles deteriorated the magnetic properties. There is remarkable consistency in magnetic behaviours and properties such as initial/incremental permeability values between the measurements by different techniques. This behaviour has been ascribed to the similar underlying domain processes and hence similar selected microstructural features that are affecting the domain processes.

5. References

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