

Review

An Overview of Non-Destructive Testing of Goss Texture in Grain-Oriented Magnetic Steels

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Abstract: Grain oriented steels are widely used for electrical machines and components, such as transformers and reactors, due to their high magnetic permeability and low power losses. These outstanding properties are due to the crystalline structure known as Goss texture, obtained by a suitable process that is well-known and in widespread use among industrial producers of ferromagnetic steel sheets. One of the most interesting research areas in this field has been the development of non-destructive methods for the quality assessment of Goss texture. In particular, the study of techniques that can be implemented in industrial processes is very interesting. Here, we provide an overview of techniques developed in the past, novel approaches recently introduced, and new perspectives. The reliability and accuracy of several methods and equipment are presented and discussed.

Keywords: non-destructive techniques; grain oriented electrical steels; electron back-scattering diffraction; magneto-optical Kerr effect; Bitter pattern technique; lag angle detection method



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1. Introduction

Rotating electrical machines such as motors and generators, and static electrical machines such as filtering inductors and transformers, are widely used in energy delivery systems and power conversion apparatus. Their efficiency plays an important role in energy consumption. Intense research activity is dedicated to reducing the power losses in such equipment; in particular, the power losses in the ferromagnetic cores have been studied intensively from a metallurgical point of view. The material used in such devices is generally silicon iron steel (FeSi) with different compositions and textures, a particular version of which was presented by Norman P. Goss in 1935 [1]. He developed a texture, called the Goss texture, with single crystal properties obtained by means of proper hot rolling, heat treating, and cold rolling. This type of steel sheet shows low losses and very high permeability in the rolling direction. This texture is nowadays used for transformers and inductors where the magnetization processes are mainly directed in a specific direction. The texture structure can be represented by specific indices such as Eulerian angles, rotation axis and rotation angle, crystal direction and angles, Miller indices, etc. All these representations are presented and explained in the specific literature, such as [2]. One of the most used representations for the Goss texture is based on the Miller indices, particularly indicated as (110)[001], where the index (110) indicates the crystallographic plane parallel to the laminated steel plane, while the index [001] indicates the crystallographic direction parallel to the rolling direction. The lattice of FeSi alloys has a body-centered cubic (BCC) cell with three magnetic easy axes parallel to the three crystal edges. The indices (110)[001] indicate that one of the cube edges (z-axis) is parallel to the rolling direction, and the other two edges (x and y-axis) are at 45 degree angles from the laminated steel plane. In the literature, there are several papers presenting the specific procedure to develop a Goss texture [3–6], and several others indicating how this texture can affect the magnetic behavior of the material [7,8]. These aspects are fundamental for the design and optimization of electrical machines and magnetic components; indeed, many works present experimental

characterizations and modeling of grain oriented electrical steels (GOES) where the Goss texture has to be assessed to ensure a certain magnetic behavior. The papers [9–15] summarize the research work developed in the recent years by Cardelli et al., in which the authors propose a vector generalization of the so called scalar Preisach model to simulate the magnetization processes of soft ferromagnetic materials, and in particular, for GOES. This type of model uses a mathematical operator called a hysteron, which is a two-value operator defined on the scalar domain of the exciting field. The vector extension, able to simulate anisotropic materials such as GOES, uses a vector hysteron defined on the two- or three- dimensional domain of the excited vector field. Two other possible approaches to simulate soft magnetic materials as GOES are presented in the papers [16,17]. In the first, the Jiles Model is proposed and evaluated to analyze the parameter identification problem, while in the second the neural network approach is presented as a general way to simulate hysteresis phenomena. The properties of soft magnetic materials are modeled also in these works [18,19], where the proposed mathematical formulation also takes into account the temperature. From an engineering point of view, very interesting works are presented in the papers [20–26], where the energy efficiency and the performance of different kinds of devices and apparatus involving soft magnetic components such as GOES, are detailed, analyzed, and evaluated.

In this paper we present an overview of different methods that can be used to analyze the structure and characteristics of a Goss textured iron sheet. In sections two and three, the use of electron back-scattering diffraction (EBSD) and the magneto-optical Kerr effect (MOKE) are presented for specific assessment of GOES sheets. They are very effective, but also very complex and expensive because they necessitate the use of sophisticated procedures and equipment. In sections four and five, we present two other techniques, the modified Bitter pattern technique (MBPT) and the lag angle detection method (LADM). These are less accurate, but their implementation is much simpler. Finally, the conclusion section contains specific discussion regarding the presented methods and some further developments dedicated to non-destructive techniques for Goss-textured materials that can be useful during manufacturing processes.

2. Electron Back-Scattering Diffraction

EBSD is used to detect the crystal lattice orientation of many crystalline and polycrystalline materials; a complete description of this method and evaluations of its accuracy are presented in [27].

Many specific applications of EBSD can be found in the literature. In [28], the authors use this method to obtain a detailed microstructural characterization of nickel-based superalloys, which are extensively used in the aerospace and power generation industries. In [29], the authors use EBSD images to display the processes of the eutectoid phase transformation of stainless steel. Other examples of EBSD applications can be found for a wide range of different materials, such as in the characterization of the microstructures and textures of vapor-deposited chemical coatings [30], lath martensite [31], and alkali halide crystals [32].

In particular, EBSD is one of the most used methods to assess the quality of the Goss texture of FeSi steel sheets. The correspondence between the crystal orientation of the bulk material under test and the Miller indices (110)[001] can be evaluated. Figure 1 illustrates a cubic crystal of FeSi sheet with the Goss texture orientation. It is possible to see the crystal plane (110) parallel to the sheet plane, and the crystal direction [001] parallel to the rolling direction. The results of the EBSD tests are often represented by a particular graph called a pole figure. The Miller indices indicated above correspond to a specific pole figure, such that an accurate evaluation of the orientation of the Goss texture is achievable by means of the EBSD test. The pole figure indicates the orientation of a particular crystal plane, if we take into account a sphere with the center on that plane, the intersection of the sphere and the plane is a circle, and the intersection of the normal line of the plane and the sphere is the pole. If we represent the circle in a two-dimensional plane and the stereographic

projection of the pole on that, we obtain a pole figure. In Figure 2a,b there are pole figures about the (001) and (110) planes of the Goss orientation indicated in Figure 1. The circle is the intersection between the reference plane and the sphere, while the points are the stereographic projections of the poles on the reference plane. The poles number more than one because the total possible rotations of the crystal coordinate system ($x'y'z'$) are taken into account.

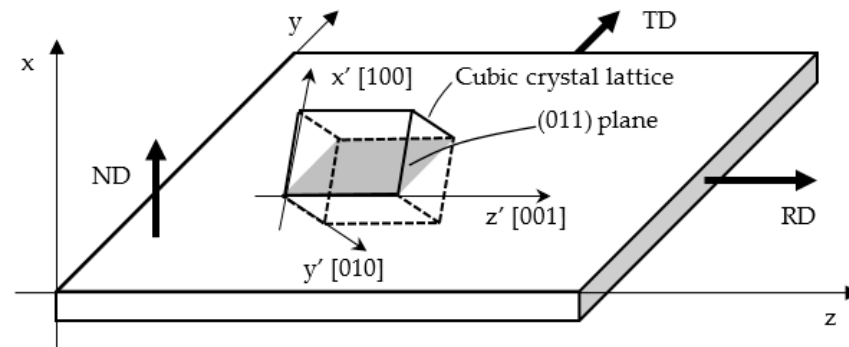


Figure 1. Crystal orientation of FeSi steel sheet with Goss texture corresponding to the Miller indices (110)[001].

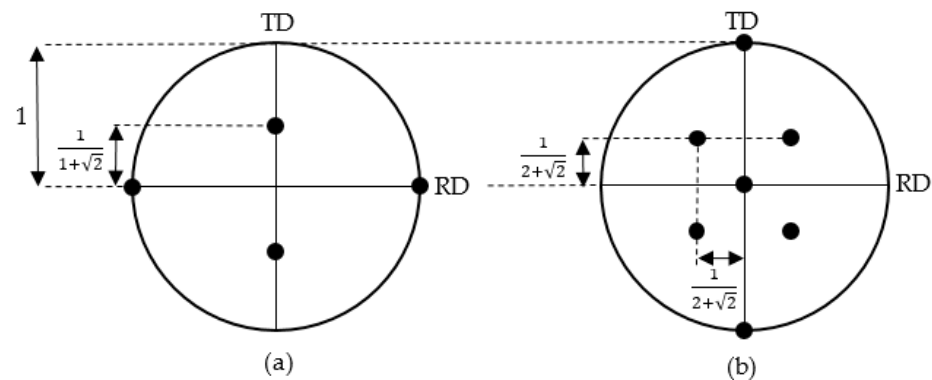


Figure 2. Pole figures corresponding to the Goss texture represented in Figure 1. (a) Crystallographic plane (001), (b) crystallographic plane (011).

The positions of the black points (pole stereographic projections) shown in Figure 2 are evaluated by a mathematical elaboration starting from the Goss orientation described in Figure 1 [2]. An example of actual pole figures detected in a GOES sample with Goss texture is presented in the paper [6] (p. 617) and reported here in Figure 3. The authors present a pole figure with the results of an EBSD analysis; the pole projections are in agreement with Figure 2 above; in particular, the measured data present a distribution of the pole projections around reference positions (points in Figure 2). The distribution of the pole projections indicates an incomplete alignment of the grains taken into account.

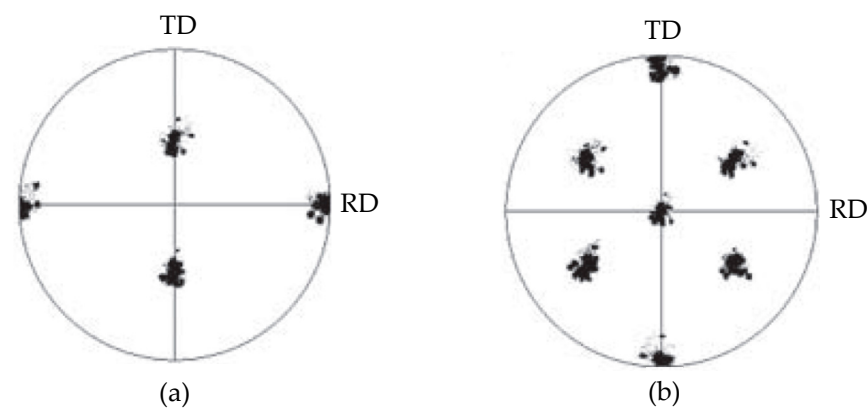


Figure 3. Pole figures measured in a GOES sample with Goss texture, presented in the paper [6] (p. 617). (a) Crystallographic plane (001), (b) crystallographic plane (011).

Drawing from that pole figure, a suitable mathematical computation can be used to identify the grain orientation, and in particular, the orientation distribution function $f(g)$ can be computed as indicated below:

$$\frac{dV}{V} = f(g)dg \quad (1)$$

$$dg = \frac{1}{8\pi^2} \sin\Phi \, d\Phi d\varphi_1 d\varphi_2 \quad (2)$$

where dV is the totality of all volume elements of the samples that possess the orientation g within the element of the orientation dg , V is the total sample volume, and $(\Phi, \varphi_1, \varphi_2)$ are the Euler's angles [2]. This function indicates the amount of the material volume fraction with the crystal lattice oriented in a certain direction.

The identification of that function, using the experimental data, is a complex procedure and still an open problem from a mathematical point of view. This issue involves several subjects, among them the sampling accuracy. The paper [33] proposes a new statistic for assessing the quality of sampling intended to be used for any continuous distribution. Depending on the sample size, the proposed statistic is operational for known distributions (with a known probability density function) and provides the risk of error while assuming that a certain sample has been drawn from a population. Another approach is proposed in the paper [34], where the authors present a statistic and a test intended to be used for any continuous distribution to detect outliers by constructing the confidence interval for the extreme value in the sample at a certain (preselected) risk of error, and depending on the sample size. Another issue is the choice of proper distribution function, about which the papers [35] and [36] have proposed interesting approaches.

Taking into account the texture analysis of ferromagnetic steel sheets, some very interesting examples of grain orientation evaluation are presented in the papers [37,38]. In [38], the authors describe some EBSD tests for two different materials, the conventional grain-oriented (CGO) steel and the high-permeability grain-oriented (HGO) steel. An average misalignment of 7 degrees for CGO and of 3 degrees for HGO was detected for the [100] axis with respect to the rolling direction. Many other papers can be found in the literature regarding Goss texture detection by means of the EBSD method; in general, they present a test sequence that describes the texture evolution during the manufacturing process, step by step. The aim is to understand how the different treatments can affect Goss texture quality; some examples are presented in these papers [4–6,8,39].

3. Magneto Optical Kerr Effect

The MOKE measurements are exploited to observe the magnetic domains of a magnetic material. This method is based on the detection of the change in polarization of a light beam when reflected by a magnetized material. In general, an incident beam with linear

polarization on a magnetic material is reflected with elliptical polarization with different aspect ratios and orientations for different magnetization states of the target. In this way, for instance, parallel and antiparallel domains can be easily detected along with their movement during the magnetization processes. In the advanced MOKE measurements, a digital camera is used to display directly the images of the magnetic domains. A complete and detailed overview of this type of technique is presented in [40]. The authors present the fundamental concept and advances in methodology and applications for bulk and thin-film materials. In particular, they indicate how this method can be useful for magnetic domain analysis of GOES and provide some measurements. Images of the magnetic domain distribution during different magnetization processes can provide important information about a material's characteristics. For instance, in a demagnetized GOES sample, the parallel and antiparallel domains inside the grains should be aligned; usually few degrees of misalignment at most is expected, as indicated in the sketch shown in Figure 4a. Light and dark shades indicate the parallel and antiparallel domains of a demagnetized GOES sample inside different grains. The irregular line indicates the boundary between two grains, and the grain dimension is generally on the order of 10 mm. Using MOKE measurements, this assessment is feasible, and in fact, G. L. Houze presented one of the first works on this issue in 1967. The author shows a picture of two adjoining grains of a (110)[001] FeSi sample obtained by means of the MOKE measurement [41] (p. 1091). The picture is shown here in Figure 4b. It is possible to observe the grain boundaries and a quite-evident misalignment of the domain orientations. This picture indicates a misalignment of the grain lattice; in particular, the crystal direction [001] of a grain is not aligned with that of the next grain (refer to Figure 1). No information is available for the (110) plane orientation.

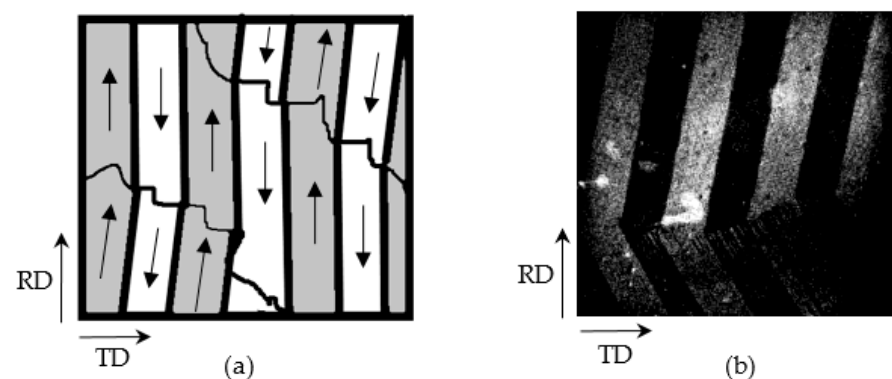


Figure 4. Expected magnetic domain pattern for a GOES. (a) Sketch of the domain orientation around the grain boundaries; (b) image of the domain orientation around the boundary between two grains of a (110)[001] FeSi sample [41] (p. 1091).

Many later papers exploiting MOKE measurements to analyze the magnetic behavior of the GOES have been published. The main purpose of these works was to generate images of the magnetic domain distribution of GOES samples under mechanical stresses to understand how they can affect the magnetic behavior of the material. The authors of [42–45] presented domain distribution images of GOES samples under different compression strengths, while [46] represented and analyzed the domain pattern around the circular holes made on GOES laminas, such as in the practical applications. One of the most relevant results is the image representation of a new type of magnetic domain known as the lancet domain. These appear near the grain boundary; their main characteristic is the orientation out of the sample plane. The presence of these domains depends on the shape and size of the crystal grains, the magnetization state, and the mechanical stress applied. It turns out that the lancet domains can reduce the magnetic performance of the steel sample [47,48].

Their typical geometry is presented in Figure 5a, where light and dark areas indicate the parallel and antiparallel domains. The top sketch shows the sample plane parallel to

the rolling direction (RD) with the presence of antiparallel triangular domains. The bottom sketch shows the sample cross-section parallel to the normal direction (ND); here the domains are oriented out of the sample surface. In Figure 5b, we show a picture presented in the paper [47] (p. 3577); the authors presented a MOKE measurement of a GOES sample near the grain boundary, and the results indicate the typical lancet domain structure.

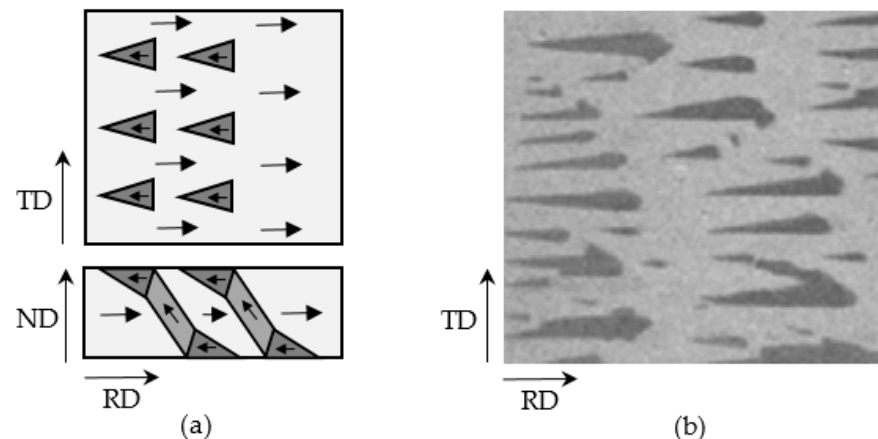


Figure 5. Lancet domains for GOES. (a) Sketch of the typical lancet domain orientation around the grain boundaries; (b) image of the lancet domains of a (110)[001] FeSi sample [47] (p. 3577).

One of the most important challenges for the MOKE technique is the image quality improvement, particularly for the low magnetic domain contrast. This goal is achievable by means of various techniques, such as by increasing the signal-to-noise ratio, but also by using suitable mathematical elaborations. Digital image processing (DIP) is deeply explored to render MOKE results more clear and understandable. For instance, one of the most simple cases is represented by the differential imaging of the same magnetic state.

$$MO = \Delta I(x, y) = I'(x, y) + I''(x, y) \quad (3)$$

where the magneto optical image MO is obtained as a combination of two images I' and I'' , of the same sample area, using two different light polarizations. The papers [49–51] give some examples of advancements in these methods.

4. Modified Bitter Pattern Technique

The Bitter pattern technique was presented by F. Bitter in 1931 [52]. This method is used to detect inhomogeneities in the magnetization of ferromagnetic materials. In particular, the images of magnetic domain patterns are produced by magnetic particle agglomerates that are in suspension in a liquid. Later, this method was used in many applications, among them the detection of magnetic domains in GOES samples. For this context, the so-called modified Bitter pattern technique (MBPT) was developed and nowadays is widely used as a non-destructive technique (NDT) by the producers of FeSi steels with Goss texture. The fundamentals and technical details of MBPT are presented in the paper [53], where an interesting comparison with EBSD and MOKE measurements is presented. The MBPT uses an external exciting coil with the axis perpendicular to the sample surface. Inside the exciting coil, parallel to the sample surface, are two transparent plastic membranes with a liquid inside. A certain quantity of magnetic powder is in suspension inside the liquid. The effect of the exciting coil is to increase the stray field located above the domains and improve the image resolution of the domain patterns in comparison with the conventional Bitter pattern method, where the external field is not used. The liquid is usually ethylene glycol, and magnetite is the magnetic powder in suspension. An example of the magnetic domain pattern for a GOES using the MBPT is presented in Figure 6. Here we show two pictures presented in the paper [54] (p. 137).

Figure 6a shows an MBPT-based commercial domain viewer placed on a GOES sample, while Figure 6b shows a zoomed section of the domain pattern image obtained.

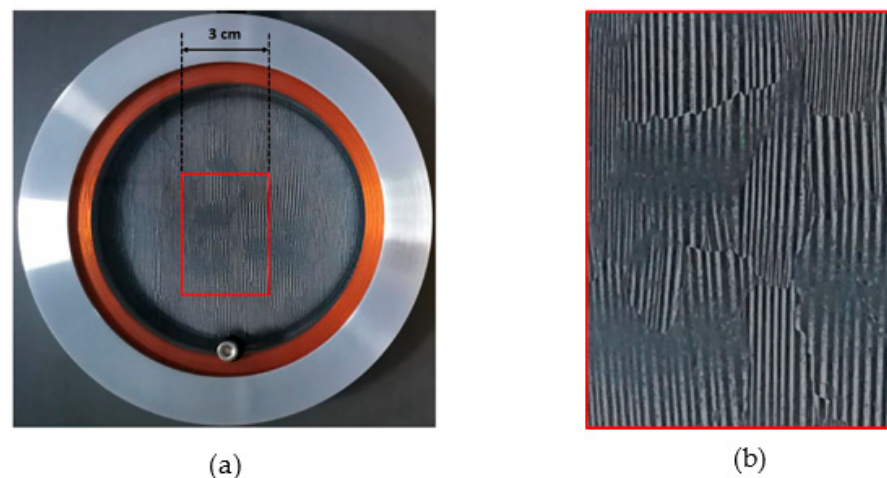


Figure 6. GOES domain pattern detection by means of MBPT. (a) Commercial domain viewer Brockhaus DV 90©, (b) zoomed view of the domain pattern image, [54] (p. 137).

It is possible to see the grain boundaries and the domain orientations that indicate grain lattice orientation. In particular, the [001] crystal direction is assessed for each grain, while no information is available for the (110) plane orientation (refer to Figure 1). We note here that detection is performed without removing the coating; surface cleaning is not necessary for this method.

An interesting approach based on DIP is presented in the papers [55,56] to evaluate the magnetization process of different ferromagnetic materials, including soft iron, starting from the images measured by MBPT. In the proposed technique, the computed average pixel value of an entire domain image corresponds to a normalized value of the flux density in the magnetic material. Therefore, nonlinearity and hysteresis can be displayed and analyzed.

5. Lag Angle Detection Method

Recently a new method has been introduced for Goss texture assessment, and is based on the measurement of the lag angle between the applied magnetic field vector and the corresponding material magnetization vector. The fundamentals of this method are described in detail in the papers [54,57,58]. Given an FeSi sheet sample with perfect Goss texture, as represented in Figure 1, there is a particular relationship between the applied magnetic field and the corresponding magnetization orientation. When we apply a rotational magnetic field vector H , parallel to the crystal plane (011), with the amplitude high enough to create a saturation region in the material, the material magnetization vector M rotates consistently. The lag angle $\Delta\vartheta$ between H and M becomes zero for eight particular orientations in comparison with the crystal direction [100]. These orientations are $0, 0 \pm 55.6, 0 \pm 90, 180 \pm 55.6$, and 180 degrees. This assumption has been theoretically and experimentally proved. Starting from that, the Goss texture of a sample can be assessed by measuring the lag angle $\Delta\vartheta$ during a rotational magnetization process. A suitable data processing of the zero crossing position of the lag angle provides the actual orientation of the crystal lattice of the sample under test. In order to make this method non-destructive, a suitable measurement of the lag angle must be performed. Indeed, if on one hand the magnetic field vector can be determined by contact-less measurement techniques, on the other hand the evaluation of the magnetization vector is more problematic. However, because only the direction (angle) of the magnetization vector matters in the calculation of the lag angle, a contact-less measurement technique can also be exploited to evaluate the angle of M . As described in [41], the magnetization direction is obtained by the difference

between the magnetic field applied in the free space and the magnetic field when the sample is present, under the same instantaneous values of the excitation currents. To do that, a circular sample has to be used in order to avoid the generation of shape-anisotropy effects, and a suitable numerical feedback technique must be applied, as indicated in [54]. An example of the lag angle measurement along a rotational magnetization process for a FeSi sample with Goss texture is shown in the paper [54] (p. 141) and reported here in Figure 7.

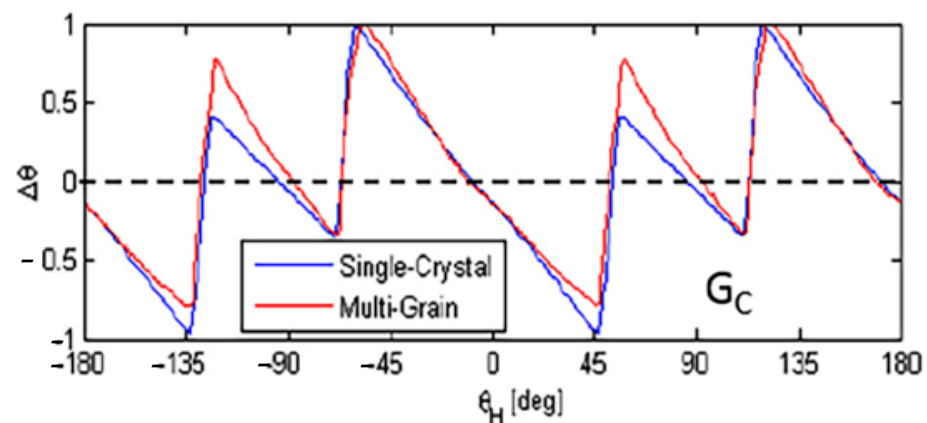


Figure 7. Goss texture evaluation by means of LADM-based measurements of the lag angle between H and M during rotational magnetization of a GOES sample [54] (p. 141).

The blue and red traces indicate, respectively, the lag angle values during a rotational magnetization of a single grain sample and a multiple grain sample. The zero crossing points of the lag angle $\Delta\theta$ are not in correspondence with the orientation indicated above. From this value it is possible to calculate the actual lattice orientation, hence possible to provide an evaluation of the Goss texture of the sample under test. In [54], the authors provide a detailed description of the mathematical computation, which is based on the physical model of Landau free energy.

6. Discussion and Conclusions

EBSD is very accurate and reliable for the complete detection of the crystal lattice orientation of a FeSi sample. The orientation of the [100] crystal direction and the (011) crystal plane can be measured for each material grain. There are some drawbacks; the equipment involved in the experimental setup is very complex and expensive, the method is quite destructive, and a small sample (with dimensions of a few centimeters) with a polished surface is needed for accurate measurements. Therefore, the surface coating of the GOES sample has to be removed and only a small part of the material can be assessed in each test session. The MOKE measurement is very accurate and useful for the detection of the domain patterns for different magnetization and stress states. It can reveal the grain dimensions and boundaries, possible defects, and domains oriented out of the sample plane, such as the lancet domains. It detects only the [100] direction of a grain lattice; no information about the (011) plane can be obtained. Additionally, for that method the equipment involved in the experimental setup is very complex and expensive, and the sample under test has to be small (dimensions of a few centimeters) and polished. The MBPT is adequate for the detection of large (tens of centimeters), domain patterns, grain sizes, and boundaries. The equipment involved is very simple and less expensive in comparison to the equipment involved in the methods described above. This method is not destructive, and allows analysis of large samples without removal of their surface coating. Only a rough evaluation of the [100] direction of the grain lattice can be obtained; no information about the (011) plane is available. The LADM is a promising technique recently introduced. The experimental equipment involved is simpler and less expensive than that used in the EBSD and MOKE methods. Measurements of the orientation of both

[001] direction and (011) plane are possible. The sample has to be small and disk-shaped (dimensions of a few centimeters), but it is not necessary to remove the sample coating. Finally we want to note that all the techniques presented in this review require suitable and advanced data-processing to improve their effectiveness and reliability; therefore, this work can provide insights for researchers able to contribute to the development of methods of soft computing, data fusion, or artificial intelligence analysis dedicated to these types of NDT.

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