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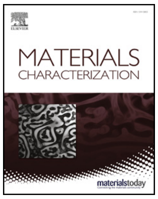

Magnetic Barkhausen noise characterization of two pipeline steels with unknown history

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ABSTRACT

Steel samples cut from two line pipes with unknown processing history were analyzed using magnetic Barkhausen noise (MBN), electron backscatter diffraction (EBSD) and Vickers hardness techniques on the pipe surface and on sections through the wall thickness. The results show that the MBN responses vary significantly not only between the two pipe steels, but also among different thickness layers of each steel. Both steels show considerable variations in MBN at different locations on the surfaces. For one steel, the surface MBN illustrates an inverse linear relationship with respect to the hardness, while the other does not depict such a relation since the variation in hardness at different locations is very small. Across the thickness, the microstructure (phase and grain size) of both steels is quite similar, but the texture shows significant differences. Again, there is a large difference in hardness across the thickness for one steel, while the other only shows very small variation in hardness across the thickness. The variations in average MBN across the wall thickness for both steels are quite large. Angular MBN measurements on the sectioned samples revealed significant discrepancies in the magnetic anisotropy in the two steels. Based on the analysis of the angular MBN data with respect to the single and dual easy axis models, one pipe can be determined to have been manufactured through a seam welding process, while the other may have been formed by spiral welding. Due to the residual stresses in the steel samples, the effect of the crystallographic texture on the anisotropy in MBN response has essentially been suppressed.

1. Introduction

Pipelines that transport oil, natural gas and other petroleum products are important infrastructure of the energy sector. The safe operation of this infrastructure is of critical importance to the economy, the public safety and the environment. A large amount of those pipelines were installed prior to the 1970's, and some basic information, e.g. the grade of the steel used to manufacture the pipe, the microstructure and stress state of the pipe, the mechanical properties and the processing history of the steel, etc., are unknown. This makes the prediction of the safety margins or the assessment of the lifetime of those pipelines extremely difficult. To help pipeline operators and regulators address this problem, non-destructive and on-site techniques were proposed as potential tools to evaluate the steel chemistry, hardness, and mechanical properties by using portable devices, e.g. optical emission spectroscope (OES), hardness tester, mechanical property tester [1,2], etc. However, those methods could not provide information regarding the stress state, microstructure, grain size or crystallographic texture, which are important factors influencing the mechanical properties and the reliability of the pipes. Thus, an on-site technology that can rapidly evaluate the stress state and microstructural features without extensive sample preparation or time-consuming testing is highly demanded.

Magnetic Barkhausen noise (MBN) analysis [3–7] is a relatively new technique that is able to quickly obtain information regarding both the microstructure and stress state in ferromagnetic materials, and is thus a potential tool for such testing. MBN is a non-destructive technology, and it does not require extensive sample preparation. The testing can be completed in a very short time (e.g. a few seconds), and is a promising technique for the evaluation of existing pipelines. In addition, a unique feature of the MBN technique is its ability to conveniently characterize the magnetic anisotropy of ferromagnetic materials caused by either stress or crystallographic texture, or both. A few studies [8–10] have been carried out to correlate the MBN signals measured in specific directions in the sample to the magnetocrystalline anisotropy energy (also known as crystal anisotropy energy [11]), the latter being able to be calculated from texture measurements (x-ray diffraction or electron backscatter diffraction) using the following equation [11]:

$$E = K_0 + K_1(\cos^2\alpha_1\cos^2\alpha_2 + \cos^2\alpha_2\cos^2\alpha_3 + \cos^2\alpha_1\cos^2\alpha_3) + \ldots \qquad (1)$$

where K_0 and K_1 are constants related to a particular material, and α_1,

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α_2, and α_3 are the angles between the magnetization direction and the crystal axes. It was found that the MBN root mean square value corresponding to the section from the saturation to remanence in the hysteresis loop had a strong correlation to the average magnetocrystalline anisotropy energy (MAE) [8].

In this paper, a texture factor, i.e. the minimum angle between the magnetization direction and the crystal axes weighted by the intensity of the orientation, was used to indicate how well the crystals in the sample were aligned to the magnetization direction [12–14]. Unlike the MAE where the angles between the magnetization direction and the crystal axes are embedded in the cosine-squared functions, thus the direction of the overall easy axis of the crystals is not obvious, the texture factor can directly show the angle between the magnetization direction and the overall easy axis of the crystals. For a single crystal, the smallest value of the texture factor is 0 (when one of the crystal axes is parallel to the magnetization direction), and the largest value is 54.7° (when one of the ⟨111⟩ directions is parallel to the magnetization direction). For polycrystals, the texture factor falls in between 0° and 54.7°, and the smaller the texture factor, the closer the overall easy axis of the crystals to the magnetization direction.

Attempts were made to characterize the magnetic response of pipe steel samples cut from existing pipelines (chemistry and history unknown) using MBN. The results were then assessed against the properties measured by conventional techniques such as hardness, grain size and crystallographic texture. The steel samples were first analyzed using OES to obtain the chemical compositions. A portable hardness tester was then used to obtain the hardness values on the surfaces of the samples. The MBN measurements were conducted at the same spots as for hardness testing, and were then compared to the hardness values. Sections were also made in the wall thickness direction of the samples and the microstructure and texture at each layer were characterized. These were then compared with the MBN results obtained from the same spots, aiming to establish correlations between the MBN and the microstructure, texture, and hardness. In addition, angular MBN was obtained on the surface of each thickness layer, and the anisotropy in MBN was analyzed with respect to the texture factor that estimates the magnetocrystalline easy axis. The processing history of the pipe steel samples was determined based on the texture and the analysis of the angular MBN data with respect to existing theoretical models.

2. The Magnetic Barkhausen Noise Method

When magnetized by a changing magnetic field, the hysteresis response of a ferromagnetic material is actually characterized by a sequence of discontinuous movements of magnetic domain walls across pinning sites in the material, which produces a noise-like signal known as the Magnetic Barkhausen Noise (MBN) [15]. The analysis of MBN signal is one of the non-destructive testing techniques utilized to detect the fracture, hardness, grinding burns, inclusions and voids of ferromagnetic materials [15]. This noise is dependent on the characteristics of the domain walls which may be affected by material state and properties such as fatigue [16,17], applied stress [18,19], residual stress [20,21], grain size [22,23], surface condition [24,25], composition [26,27], hardness [28–30], etc. Moreover, angular MBN signal (i.e. the dependence of the MBN on the magnetization direction) can provide information regarding the magnetocrystalline anisotropy and the processing history of the material [15,31]. The magnetic anisotropy of the material is dependent on the direction of the applied (or residual) stress as well as the crystallographic texture, both resulting in the alignment of the net easy axis (⟨100⟩ for bcc iron) in certain directions. Because of the dependence of the MBN signal on several material characteristics altogether, the effect of individual material feature on the MBN is usually difficult to distinguish. Despite this limitation, the analysis of MBN signal showed a number of applications in the manufacturing industry [32] as well as in failure analysis [33].

A number of studies have been carried out [34–36] to characterize the MBN response of pipeline steels. Krause et al. [37] analyzed a 2% Mn pipeline steel on both surfaces of the pipe and established a cosine-squared function relating the MBN energy to the magnetization direction. They also established a theory [37,38] for the characterization of single and dual easy axis systems for pipeline steels. For the purpose of pipeline non-destructive inspection, the relation between the MBN signal and the microstructural features of the material is an important aspect to be investigated, as these will affect the mechanical properties of the pipe. Although the use of MBN signal for material characterization has been around for decades [39–41], the application of this technique for pipeline non-destructive testing is still limited due to the combined effects of all the structural and stress features on the MBN. To assess the applicability of MBN in pipe inspection, the present work focuses on the analysis of the MBN signal across the thickness of two pipeline steels in an attempt to establish relationships between the MBN response and the stress, microstructural and crystallographic features of the material.

3. Experimental Procedure

Two steel samples (~6 cm × ~7.5 cm) were directly cut from two line pipes (sources and history unknown), and the samples were first examined using optical emission spectroscopy (OES) to determine the chemical compositions (Table 1). Both steels contain very low carbon (0.033–0.04%) and some minor alloying elements (mainly Mn). The largest difference is in the content of vanadium, where Steel II contains > 10 times than Steel I. However, the absolute percentage is very low, i.e. 0.003–0.041%. Steel I has slightly more silicon than Steel II, but its carbon content is slightly lower. Hardness tests were first performed on the outer surface (after grinding using SiC papers up to 600 grit) of each sample on four different spots (Fig. 1a and b). MBN measurements were then conducted on the same spots at various directions, i.e. 0°–360° (with a 30° interval) with respect to the pipe axis direction (AD). These tests provided an estimation of the relation between the hardness and the MBN on the pipeline outer surface, which would be the surface to be tested during on-site pipeline inspection.

In order to investigate the variation of the MBN signal with respect to the pipe wall thickness, 4 rectangular samples (20 mm × 20 mm × 4 mm) were sectioned at different thicknesses from each of the two steel samples (Fig. 1c). The microstructure, texture, hardness and MBN were measured on each section. The sectioning of the rectangular samples from the pipe samples is schematically shown in Fig. 1c. For Steel I, four samples were sectioned at 0, 4.2, 8.3 and 15.5 mm from the outer surface. For Steel II, another set of four samples were sectioned at 0, 4.6, 9.2 and 13.1 mm from the outer surface. Before hardness and MBN tests, all these samples were ground using SiC papers up to 800 grit.

For hardness measurements, a portable Krautkramer Through-Indenter View (TIV) hardness testing system (GE Inspection Technologies) [42] was used. At each spot, the hardness test was

Table 1
Chemical compositions of the two pipeline steel samples (wt%).

Steel ID	C	Si	Mn	Cr	Ni	Mo	Cu	Al	Nb	V	Ti	P	S
Steel I	0.033	0.19	1.68	0.013	0.25	0.20	0.11	0.030	0.051	0.003	0.015	0.010	< 0.001
Steel II	0.040	0.15	1.61	0.019	0.27	0.20	0.15	0.022	0.073	0.041	0.010	0.012	0.001