NONDESTRUCTIVE MONITORING OF PEARLITE DEGRADATION IN MEDIUM CARBON STEELS BY MAGNETIC BARKHAUSEN NOISE METHOD

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ABSTRACT

Cementite in steel microstructures exits in various forms such as lamellae in pearlite after normalizing, or nano-size particles in ferrite matrix after quenching-tempering, or large spheroidal particles in ferrite matrix after spheroidizing heat treatment. Any alteration in the cementite morphology influences the strength and hardness of pearlite that exists in most of the steel structures used in wide range of industrial applications. For instance, spheroidizing heat treatment is intentionally applied to increase the cold formability and machinability. On the other hand, there is a serious risk for the structural integrity of boiler tubes and steam pipes that operate at elevated temperatures for long periods due to degradation of pearlite by formation of spheroidal cementite. This study aims to investigate the applicability of Magnetic Barkhausen Noise (MBN) method for nondestructive detection of the changes in pearlite caused by prolonged heating of medium carbon steel near the eutectoid temperature. The microstructures were characterized by metallographic investigations, hardness and MBN measurements. It was observed that MBN emission is very sensitive to the alteration in the spheroidization level which makes it a candidate for nondestructive determination of the pearlite degradation.

Keywords: Steel, Pearlite degradation, Nondestructive evaluation, Magnetic Barkhausen Noise

1. Introduction

The steels having pearlite in their microstructure are widely used in various industrial applications since pearlite is tough, strong, and sufficiently ductile. Pearlite forms during cooling by the cooperative growth of ferrite and cementite (Fe₃C) in the prior austenite grains. It has a distinctive appearance created by the thin lamellar bands of ferrite and cementite. In three dimensions, however, a pearlite colony is an interpenetrating bi-crystal of ferrite and cementite.
Alteration in the pearlite morphology influences the strength and hardness of steels. During long-term exposure of steels to elevated temperatures, the shape of the cementite gradually transforms into granular carbide. Mechanical properties of the steels decrease with increasing spheroidization level, the dilution degree of alloying elements in solid solution, and grain coarsening.

There are two opposite industrial aspects for the formation of spheroidal cementite: The spheroidization heat treatment is commercially applied to improve machinability and formability, or to develop a suitable structure for subsequent hardening treatment by heating the medium- and high-C steels at about eutectoid temperature for sufficiently long periods. On the other hand, a serious risk for the structural integrity of the low-C low-alloy steel boiler tubes and steam pipes exists due to prolonged exposure at about 550°C. The assessment of the instantaneous condition to guarantee further safe service requires the knowledge of changes in the microstructure that might negatively influence mechanical properties such as degradation of pearlite. The critical damage mechanisms that cause deterioration of steels including spheroidization have been mentioned in some standards like API 571, API 573 and API 581. Han et al. investigated microstructure degradation in 12Cr1MoV steel, which is widely used as boiler super-heater and main steam pipes under high pressure at about 580°C. They demonstrated five levels where Level 1 refers to no spheroidization and Level 5 serious-spheroidization; the pearlite structure disappears at Level 4 and Level 5, which results in deterioration of mechanical properties and even failure [1]. Pantazopoulos et al. reported that a steel frame subjected to prolonged temperature exposure presented a reduction of tensile strength up to 33% due to microstructural degradation involving cementite spheroidization and graphite formation which risks its structural integrity [2]. Chen et al. proposed a new method for automatically detecting the pearlite spheroidization level by analysis of metallographic image mining and artificial neural networks, and verified the method by investigating ASTM A315-B, A335-P12, and A355-P11 steels used in coal-fired power plants [3]. Feng et al. reported that spheroidization of lamellar cementite also occurs in cold-drawn pearlitic steel wires during galvanizing treatment, leading to the degradation of mechanical properties [4]. Due to requirements for the components operating under heavy conditions in petrochemical and power generation industries, in-situ metallography has recently become an essential non-destructive technique for conducting the plant integrity assessments by monitoring in-service degradation of critical steel components.

Magnetic Barkhausen Noise (MBN) measurement may provide an alternative to the traditional methods for microstructure characterization of ferromagnetic materials. Ferromagnetic materials tend to minimize their internal magnetic energy by forming a multi-domain structure in which the domains have randomly distributed magnetization directions (Fig. 1).

![Fig. 1: Schematic view of magnetic domains and domain walls.](image-url)
All magnetic moments within a domain are aligned and the electron spins have the same orientation. The domain walls move in such a way that domains with a magnetization in a favourable direction grow by dominating the domains with a less favourable direction. When a domain wall is moving, it has to pass the defects in the crystal structure. Depending upon the type of the defect a local variation in the easy axis, which lowers the energy of the domain wall interacting with the defect, occurs. Also, lattice strains caused by the defect create an additional magnetic anisotropy in the structure. Thus, an extra applied magnetic field is needed to prevent the domain wall from being pinned at defects. Investigation of domain wall pinning can give information on the microstructure like second phase particles, grain boundaries, dislocations, etc. For measurement of MBN, an alternating current is fed to the magnetizing yoke to generate a changing magnetic field for the repeated magnetizing and demagnetizing cycles of the specimen. The local magnetization changes due to stepwise break away of the domain walls cause pulsed eddy currents which induce electrical voltage pulses. Capturing of these pulses with a pick-up coil leads to the Barkhausen noise signal.

MBN signals are sensitive to the changes in microstructure and residual stress state. MBN method was used to study grain boundary microstructure [6]. A linear relationship was found between MBN and hardness in martensitic steels [7]. Various studies concluded that tempering of martensite and presence of residual stresses affects MBN response as well [8-11]. Moorthy et al. reported that the size and distribution of the carbide particles strongly affect the Barkhausen signals [12]. Lo et al. observed a decrease in the peak ratio of magneto acoustic emission profile and the formation of a second peak in the magnetic Barkhausen noise profile during spheroidization of pearlitic steels [13]. Davut and Gür reported that MBN signals are very sensitive to the variations in the microstructure caused by the spheroidizing heat treatment [14]. Lo et al. investigated the ferritic-pearlitic steels and found that increasing ferrite content decreases Barkhausen activity in low-field region and causes formation of outer peaks in the MBN profiles [15]. Koo et al. showed that Barkhausen signal increases monotonically with pearlite content for both hypo-eutectoid and hyper-eutectoid steels [16].

The aim of this study is to monitor the degradation of pearlite by the MBN method. For the experimental studies, a set of medium-C steel specimens consisting of either lamellar pearlite or partially/completely spheroidized cementite in ferrite matrix was prepared by heating them near the eutectoid temperature for different periods.

2. Experimental Procedure

The specimens prepared from SAE 1060 steel were heated at 800°C for 1 hour and then furnace cooled. One specimen was kept in the as-annealed condition, and other specimens were further heated at 700°C for 24, 48 and 72 hours.

After metallographic preparation, the specimens were characterized by SEM investigations and hardness measurements.

MBN measurements were performed using commercial equipment, Rollscan 500-2. During measurements a sinusoidal cyclic magnetic field with an excitation frequency of 20 Hz was induced in a small volume of the specimen via a ferrite core C-coil. The Barkhausen signals were filtered with a band-pass filter (0.1-300 kHz), and then, analyzed. The peak magnetizing voltage was 8V and sampling frequency was 2 MHz. The MBN peak heights and corresponding magnetic field strengths, and MBN-rms (root-mean-square) values were calculated. For the sinusoidal cyclic magnetic field, the MBN-rms value corresponds to 0.707 times the MBN peak value.
3. Results and discussions

The representative SEM micrographs are given in Fig. 2 [14]. The annealed specimen (Fig. 2a) consists of 25% ferrite and 75% pearlite. Fig. 2b and Fig. 2c show partially spheroidised structures. Fig. 2d shows the microstructure of an almost completely spheroidized specimen after heating at 700°C for 72 h. To reduce the interfacial energy, cementite lamellae tend to break up into smaller particles that eventually assume spheroidal shape. Once the lamellae have broken up, the small particles dissolve, and larger particles grow [17]. The spheroidized structure is stable because the ferrite is relatively strain free and the spheroidal cementite particles have minimum interfacial area per unit volume.

![Micrographs](image1.png)

Fig. 2: Representative micrographs of the specimens.

During MBN measurements, an alternating magnetic field is induced and after the sample has been magnetized, reversal of magnetization is preceded by nucleation of domain walls, or by releasing domain walls trapped onto the pinning sites. Fig. 3 shows the curves for MBN signal versus magnetic field strength. In the annealed sample, cementite appears as lamellae in the pearlite which act as barrier to the domain wall movement. The large interfacial area of cementite lamellae, which in turn increases volume fraction of pinning sites, increases the energy loss during the magnetization. In addition, the short distance between pinning obstacles, i.e., the inter-lamellar spacing of the pearlite, restricts the movement of domain walls. The pearlitic sample has the weakest MBN peak positioned at the highest magnetic field strength since domain walls were pinned at the cementite lamellae, and the unpinning of domain walls requires a higher reverse magnetic field.

![MBN Profiles](image2.png)

Fig. 3: MBN profiles of the specimens.
As the level of spheroidization increases, MBN peak increases in magnitude and shifts to the lower magnetic field strength values. This indicates that spheroidal cementite show weaker domain wall pinning effect compared to cementite lamellae. The low surface-to-volume ratio of the spheroidized cementite decreases the effective surface area of pinning sites. In addition, average distance between pinning sites increases allowing domain walls to move more freely. Thus, a weaker magnetic field is enough for the reversal of magnetization because of easier domain wall displacements. After holding the sample at 700°C for 72 h, it was observed that cementite lamellae were almost completely transformed to the spheroidized form. This alteration results in a remarkable increase in the MBN peak height, and the MBN peak shifts to a very low magnetic field strength value.

Fig.4 shows the representative magnetic hysteresis curves of the samples. Since the MBN is derived from magnetization cycles the sum integral of rectified bursts gives a simulation of the hysteresis loop. Coercivity and remanence determined from this hysteresis loop however, cannot be used as exact values because the saturation magnetization of the whole specimen is far beyond the level reached by local MBN measurements.

The hysteresis loop is induced in the small volume due to the energy loss with the irreversible process of magnetization which is strongly related to the nucleation, annihilation and growth of domains. The remanence is the remaining magnetic induction of the material when the magnetic field is reduced to zero after the material has been induced to saturation magnetization, and it depends on the resistance of the material to spontaneous demagnetization, i.e., domain nucleation. The coercivity is the external magnetic field needed to reduce the remaining magnetic induction to zero, and it is influenced by the interactions between domain wall motion and microstructure features. From Fig.4 it is seen that as the level of spheroidization increases microstructure starts to behave magnetically soft, i.e., the hysteresis curve becomes narrower, remanence and coercivity decrease.

![Graph showing magnetic hysteresis curves](image)

Fig. 4: Representative hysteresis curves of the pearlitic and spheroidized (72H/700°C) samples.

Generally, a linear relation is expected between mechanical hardness and the peak position of the MBN. The microstructural features that impede dislocation movement, also make domain wall movement harder [18].
The regression analysis shows a good correlation between the MBN-rms value and hardness (Fig. 5). Among the specimens, the pearlitic microstructure having the maximum hardness has the lowest MBN-rms voltage. Pinned domain walls due to large surface area of cementite lamellae in the pearlite reduce MBN emission. As the spheroidization level increases MBN-rms value increases due to enhancement of domain wall displacement in contrast to the reduction in hardness.

4. Conclusions

The applicability of Magnetic Barkhausen Noise (MBN) method for determination of the pearlite degradation was investigated on the SAE 1060 steel samples which were prepared by heating near the eutectoid temperature for different periods. The microstructures were also characterized by metallographic investigations and hardness measurements. Long heating periods lead to change the cementite morphology from lamellar to spheroidal form. The ferritic-pearlitic sample has the weakest MBN peak positioned at the highest magnetic field strength since the large surface area of cementite lamellae effectively pin the domain walls. As the level of spheroidization increases, the average distance between cementite particles increases and the surface area of these particles decreases. Due to reduced effect of domain wall pinning, MBN emission increases and the MBN peak shifts to the lower magnetic field strength values; moreover, remanence and coercivity of the steel decrease while the saturation magnetisation flux increases. Also, a linear inverse relationship exists between hardness and MBN peak height. The conclusions of this particular study indicate that MBN emission is very sensitive to the alteration in the cementite morphology which makes it a strong candidate for nondestructive determination of the pearlite degradation level.

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5. References


