Proceedings of the 5th World Congress on Mechanical, Chemical, and Material Engineering (MCM'19)
Lisbon, Portugal – August, 2019
Paper No. MMME 121
DOI: 10.11159/MMME19.121

Microstructure Characterization of Heat-Treated Ferromagnetic Steels by Magnetic Barkhausen Noise Method

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Abstract **-** This paper presents non-destructive evaluation of microstructures of heat treated steels by the Magnetic Barkhausen Noise (MBN) method. Various steel specimens having different microstructures were produced by appropriate heat treatments. All specimens were characterized by metallographic examinations, hardness and MBN measurements. The results showed that MBN parameters are highly sensitive to the variations in the microstructure, and this method is a promising candidate for practical non-destructive characterization of heat treated steels.

Keywords**:** Steel, Heat Treatment, Microstructure, Non-destructive Characterization, Magnetic Barkhausen Noise.

1. Introduction

Heat treatment methods are widely used to obtain the microstructure and mechanical properties requested in the technical specifications of steel products. Utilization of practical and non-destructive methods to control of the success of the process on all products is of importance for heat treatment industry.

Magnetic parameters derived from the hysteresis loops of ferromagnetic materials is sensitive to variations in chemical composition, microstructure, hardness and residual stress state. Therefore, it might be possible to characterize the microstructure and hardness of the heat-treated ferromagnetic steels via magnetic non-destructive techniques such as magnetic Barkhausen noise (MBN) method. Internal magnetic energy of a ferromagnetic polycrystalline material is minimized via formation of magnetic domains separated by domain walls as substructures of grains. In a magnetic domain, whose size is usually between 0.1 and 1μm, the electron spins have the same orientation and magnetic moments are aligned in the easy magnetization directions dependent upon the type of crystal structure. Domains are randomly oriented spontaneously, thus, bulk ferromagnetic materials do not show magnetism unless an external magnetic field is applied.

The hysteresis curve “magnetic flux (Tesla) versus magnetic field strength (A/m)” contains very small magnetic flux jumps caused by the discontinuous motions of domain walls to pass the imperfections, i.e., dislocations, precipitates, phase interfaces, grain boundaries, in the crystal structure. When the magnetic excitation field is strong enough, the domain walls pinned by imperfections irreversibly split from the imperfection sites. This movement causes pulsed eddy currents which induce voltage pulses, i.e., MBN emission. Raw MBN data, recorded as a function of time by an appropriate sensor, consists of series of voltage pulses and associated magnetic field values. Various magnetic parameters such as MBN signal voltage, MBN signal form (amplitude versus exciting magnetic field strength) can be obtained via rectification, amplification and filtering of the raw data. The signals are derived from magnetization cycles, thus the sum integral of rectified bursts may also give a local simulation of the hysteresis loop. MBN measurement depth for practical applications varies between 0.01 to 1.5 mm. Generally, low-frequency measurements are preferred in cases where the sub-surface properties are more important than the variations in surface. Details on the fundamentals of the MBN method can be found elsewhere [1,2]. In literature it has been reported that microstructural parameters of steels such as average grain size, phases (ferrite, pearlite, martensite, tempered martensite, spheroidized cementite) affect the MBN signals [3-8]. Besides, residual stress state created by manufacturing processes has also remarkable influence on the MBN emission [9].

2. Experimental

The specimens having 5 mm thickness were prepared from a hot-rolled AISI 1040 rod. Following full austenitization at 850ºC for 0.5 hour, three different cooling paths were applied to the specimens, namely, quenching in water, cooling in still air, and cooling in the furnace. After heat treatments, the scale layers were carefully removed from the surfaces. Microstructures were characterized via scanning electron microscopy and hardness measurements. MBN measurements were carried out using the Rollscan system where a cyclic magnetic excitation field of 125 Hz having a smooth sine-waveform was induced in a small volume of the specimen.

3. Results and Discussion

Metallographic investigations showed that the quenched specimen consists of martensite whereas air- and furnace-cooled specimens contain pro-eutectoid ferrite and pearlite. However, the ferrite and cementite layers in pearlite in the air-cooled specimen are thinner than those in the furnace-cooled one. Hardness measurements supported the metallographic investigations: the highest hardness (approx. 660 HV) belongs to the quenched specimen, and the furnace-cooled specimen has the lowest hardness (approx. 180 HV). Fig.1 shows the differences in hardness values of the specimens.

The variations in the MBN emissions of the heat-treated specimens are given in Fig.2. The lowest MBN emission was recorded on the quenched specimen, and the emission increased subsequently with decreasing cooling rate, i.e., air-cooling and furnace cooling.

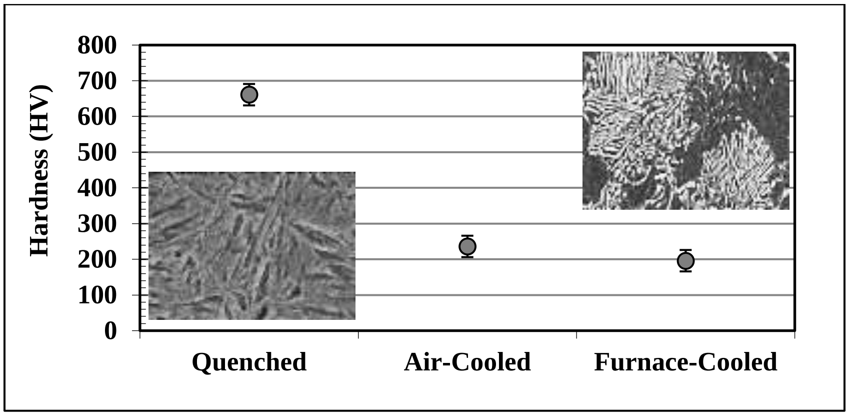

Fig. 1: Hardness and representative microstructures of the heat-treated specimens.

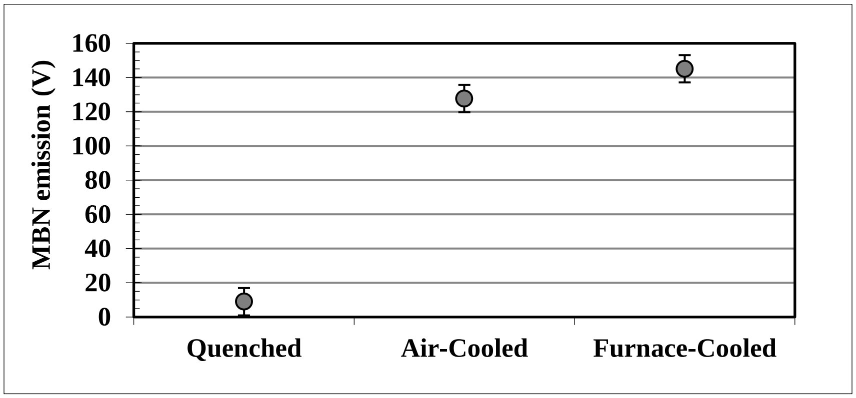

Fig. 2: MBN signal emissions of the heat-treated specimens.

Fig. 3 compares the forms of MBN signals i.e., signal voltage (peak height) versus magnetic excitation field curves, obtained for each specimen. MBN peak height is dependent upon the average jump size of domain walls whereas the magnetic excitation field corresponds to the magnetic field strength required for the splitting of domain walls from the sites pinning them.

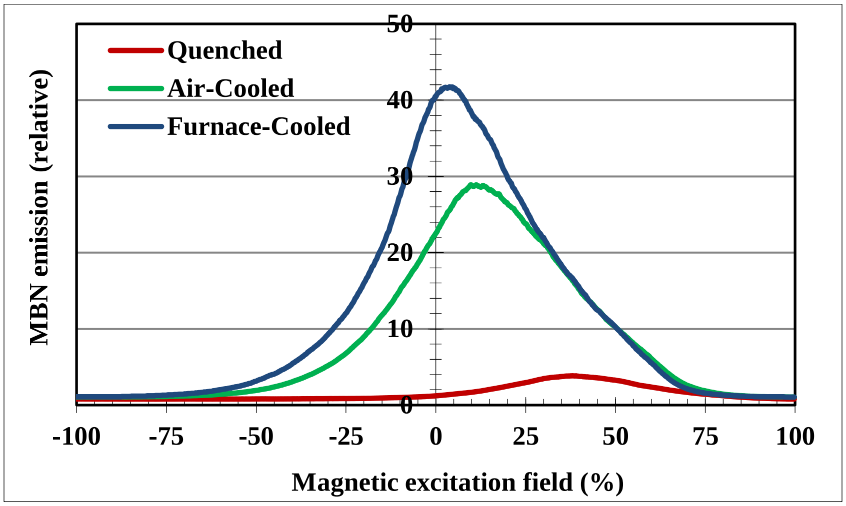

Fig. 3: MBN signal forms of the heat-treated specimens.

Among the specimens investigated, the martensitic microstructure causes the broadest MBN peak with the lowest height situated at the highest magnetic excitation field. The furnace-cooled specimen having pro-eutectoid ferrite and coarse pearlite has the strongest signal peak situated at the lowest magnetic excitation field.

For the specimens having softer phases, the MBN peak height increases and shifts to the weaker magnetic fields, and becomes narrower. When the ferritic-pearlitic specimens are compared, it is seen that the MBN emission from the microstructure containing coarse pearlite is higher than that from the one containing fine pearlite.

In martensite, the volume occupied by domain walls is very high due to very small domains caused by the needle-like structure. Besides, pinning effect of extremely high number of dislocations created during diffusionless transformation from austenite to martensite remarkably restricts the growth of domains. Thus, the reversal of magnetization requires a stronger field, domain walls can move with shorter displacements, and creation of new domain walls becomes more difficult.

The average jump size of domain walls in the ferritic-pearlitic microstructure is wider than that in the martensitic microstructure. Pearlite consists of subsequent micron-size layers of soft ferrite and hard cementite that were formed along certain crystalline orientations in the austenite grains within a very short time period via short-range diffusion of carbon atoms during cooling. MBN signal height increases with coarsening of the pearlite due to significant increase in the average jump size of domains. In addition, the magnetic excitation field required for splitting of domain walls from pinning sites, namely the borders between pro-eutectoid ferrite and pearlite regions, and interfaces between ferrite and cementite layers in pearlite, decreases remarkably.

The correlation graph between hardness and MBN emission given in Fig.4 indicates a linear relationship. MBN emission, i.e., signal height, decreases with increasing hardness. Since the types, and amounts of the phases in the microstructure directly affects the overall hardness of the specimen, variations in the hardness due to microstructure changes can also be sensitively detected by MBN measurement.

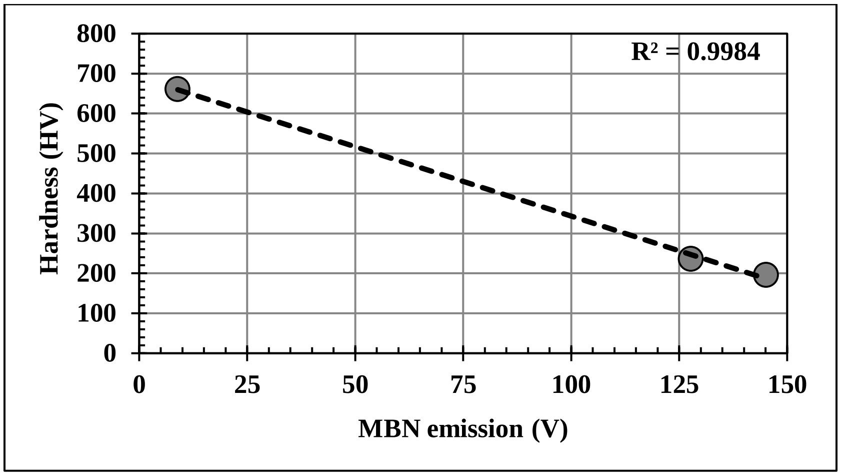

Fig. 4: Correlation between hardness and MBN emission.

4. Conclusion

For microstructure characterization of ferromagnetic steels, the Magnetic Barkhausen Noise (MBN) measurement is a promising procedure as a non-destructive alternative to the traditional destructive procedures, i.e., metallographic investigation and hardness measurement. The results of this particular study show that MBN emission is highly sensitive to the variations in the steel microstructure. By establishing the quantitative relationships between MBN parameters, microstructure and hardness, when the influence of residual stress on MBN is negligibly small, this method can be utilized effectively for reliable microstructure characterization of heat-treated steels, and also, for proving the success of the heat treatment by controlling all parts in a batch.

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