# Comparison of Magnetic Barkhausen Noise and Sound Velocity Measurements for Characterisation of Steel Microstructures

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**Abstract.** The aim of this study is to compare the effectiveness and efficiency of Magnetic Barkhausen Noise (MBN) and ultrasonic methdos for characterisation of steels. Various heat treatments were carried out on SAE 4140 steel to obtain samples with different microstructures. Application of an identical austenitisation procedure eliminated the influence of the prior-austenite grain size on the magnetic and ultrasonic parameters. Microstructures were characterised by metalography, and hardness measurements. The position of the MBN peak and the magnetoelastic parameter were evaluated by a commercial system, and sound velocities were determined by ultrasonic pulse-echo technique. The results showed that MBN method is more sensitive than sound velocity measurement for evaluating microstructure of heat treated steels.
**Keywords:** Steel, Microstructure, Magnetic Barkhausen Noise, Sound velocity

## 1 Introduction

Utilisation of non-destructive techniques for characterisation of the microstructures and determination of mechanical properties has been a challenging task for many years. Various ultrasonic and magnetic methods were developed for this purpose.

Magnetisation of a ferromagnetic material by a varying external magnetic field results in numerous jumps in random sequence, named as magnetic Barkhausen noise (MBN). The change in magnetisation takes place by the irreversible movement of the domain walls in weak fields, or by rotation of the direction of magnetisation in strong fields. Since MBN signal reflects the magnetic flux change due to the magnetic moment change during the domain wall motion, an analysis of the Barkhausen signal, in conjunction with control of the bandwidth of the detected signal, permits evaluation of changes in material condition [1,2]. A strong influence of microstructure on the MBN peak height, position, frequency range has been reported [3-7]. Studies on dual-phase steels demonstrated that it was possible to use MBN measurements to determine both the relative proportion of ferrite and martensite, and the carbon content of martensite [8]. Austenite-martensite transformation during cold working and annealing has also been investigated using MBN method [9].

In the case of ultrasonic measurements, short bursts of pulses are transferred into a sample having parallel surfaces. By monitoring the echo reflected from the back-wall, the time delay between transmission of the initial pulse and receipt of the echo is measured. Sound velocity in bulk materials mainly depends on the Young’s modulus and the density. Wave velocity varies from grain to grain due to misorientation of grains, related to variation in the elastic constant in the same direction. Previous studies have demonstrated that microstructural parameters such as average size and orientation of the grains, prior austenite grain size, and the type and volume fraction of the phases affect the sound velocity [10-13].

This paper presents a sensitivity comparison between magnetic Barkhausen noise and ultrasonic methods for the characterisation of steel microstructures. Effects of austenitic grain size and microstructural non-uniformity are negligible due to careful heat treatments.

## 2 Experimental Procedure

Specimens with 5 mm thickness were cut from the hot rolled SAE 4140 steel bars. Following austenitisation at 850$^{o}$C for 0.5 h, various heat treatments were applied (Table 1). Specimen surfaces were slightly ground to remove scale layer. Microstructures were characterised using conventional methods: metallography and hardness measurement.

**Table 1:** Heat Treatment Procedures (following austenitisation at 850$^{o}$C/0.5 h)

| | Heat treatment |
|---|---|
| a | Water quench |
| b | Water quench + tempering at 600$^{o}$C / 2 h |
| c | Holding in salt bath at 600$^{o}$C / 10 min |
| d | Holding in salt bath at 680$^{o}$C / 1 h |

MBN measurements were carried out using a commercial system (Rollscan/µscan 500). A constant pressure on the sensor was provided during measurements. A cyclic magnetic field was induced in a small volume of the specimen with a coil. A smooth sine-waveform of magnetic excitation was achieved by setting the signal amplification and the gain to 20 dB at the excitation magnetic field of 125 Hz. The position of the MBN peak on the graph of the relative r.m.s. voltage of MBN signal versus relative magnetic excitation field, and the magneto-elastic parameter (MP) were evaluated. MP value is proportional to the average value of the effective voltage measurements.

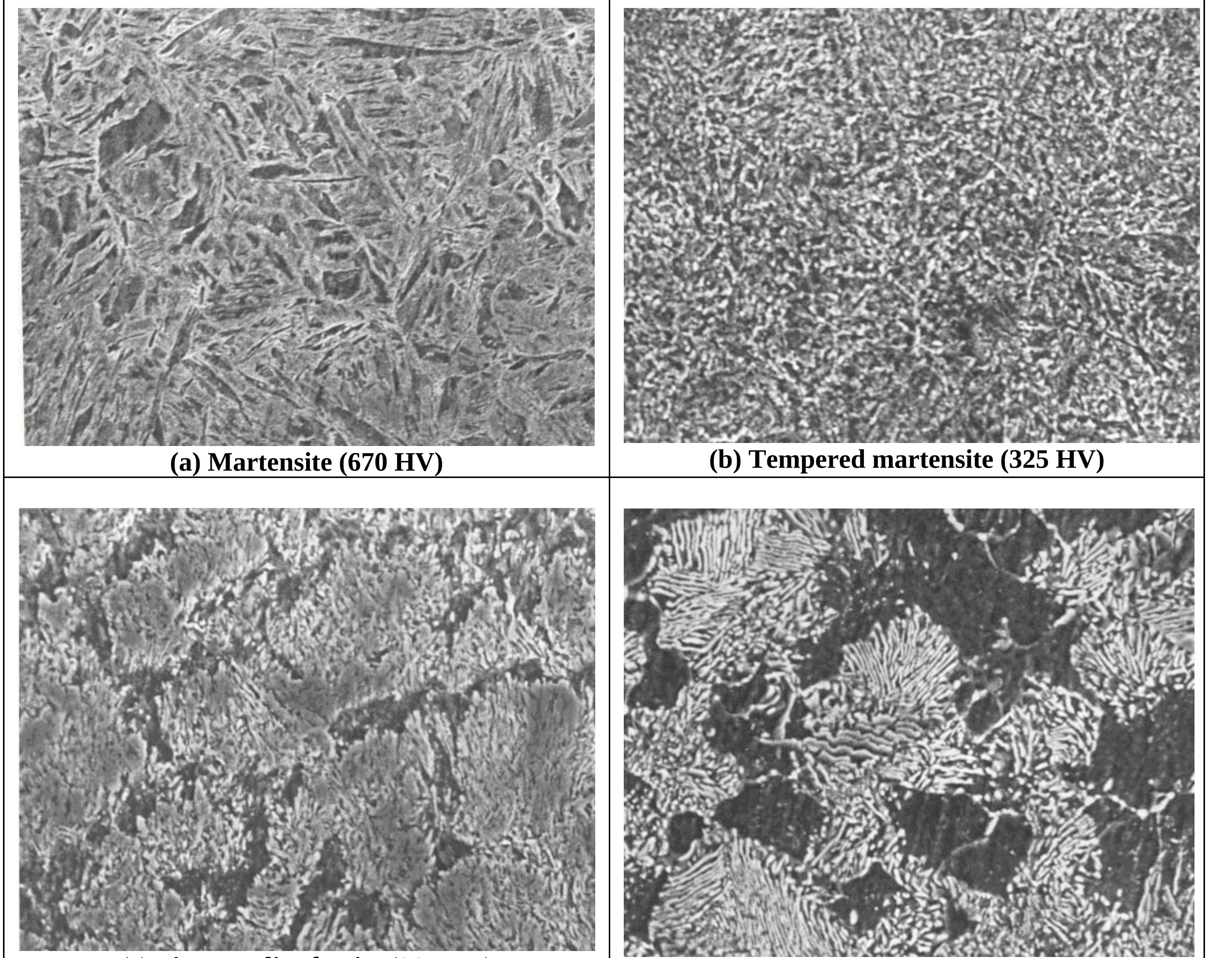
Pulse echo technique was utilised for ultrasonic measurements. Signals produced and received by a 20 MHz probe were evaluated using an analyser and an oscilloscope. Machine oil was used for coupling. The sound velocity was calculated by dividing twice the specimen thickness by the time-of-flight between the subsequent back-wall echoes.

## 3 Results and Discussion

### *3.1 Microstructure*

The evolution of the aimed microstructures throughout the samples was proven by metallographic examinations and hardness measurements. Thus, comparisons among sound velocity, MBN, hardness and microstructure became possible. The influence of retained austenite was neglected. Rolling bands and variations in grain shape do not exist. Application of an identical austenitisation eliminated the effect of prior austenite grain size on the magnetic and ultrasonic parameters.

Figure 1 gives the representative micrographs and average hardness values of the samples, indicating the achievement of the microstructures aimed. Quenched sample consists of a fully martensitic structure (Figure 1-a); 600°C-tempered sample has a microstructure of spheroidal cementite particles in ferritic matrix (Figure 1-b). Pearlitic-ferritic microstructures were obtained after isothermal treatments. Pearlite transformed at 600$^{o}$C has thinner layers of ferrite and cementite compared to those of the sample hold at 680$^{o}$C (Figure 1-c and 1-d). Thus, the main parameters influencing the nondestructive measurements are the volume fraction of phases and the size of the pro-eutectoid ferrite grains and the thicknesses of the layers in pearlite. The highest hardness value belongs to the quenched samples whereas the one consisting of coarse pearlite-ferrite has the lowest hardness.



**(a) Martensite (670 HV)**

**(b) Tempered martensite (325 HV)**

**(c) Fine pearlite-ferrite (265 HV)**

**(d) Coarse pearlite-ferrite (200 HV)**

**Figure 1.** Representative Micrographs and Hardness of the Samples

### *3.2 Barkhausen Noise Measurements*

Figure 2 shows the MP values of the specimens. Quenched structure has the lowest MP value, and the peak amplitude increases in the order of tempered martensite, fine pearlite-ferrite, and coarse pearlite-ferrite. Nucleation, annihilation and growth of domains affecting the irreversible magnetisation are dependent upon the grain boundaries, interfaces, dislocations and precipitates. The maximum MBN amplitude is a function of the jump size of domain walls, and the corresponding magnetic field represents the magnetic field strength required for the movement of domain walls from pinning sites.

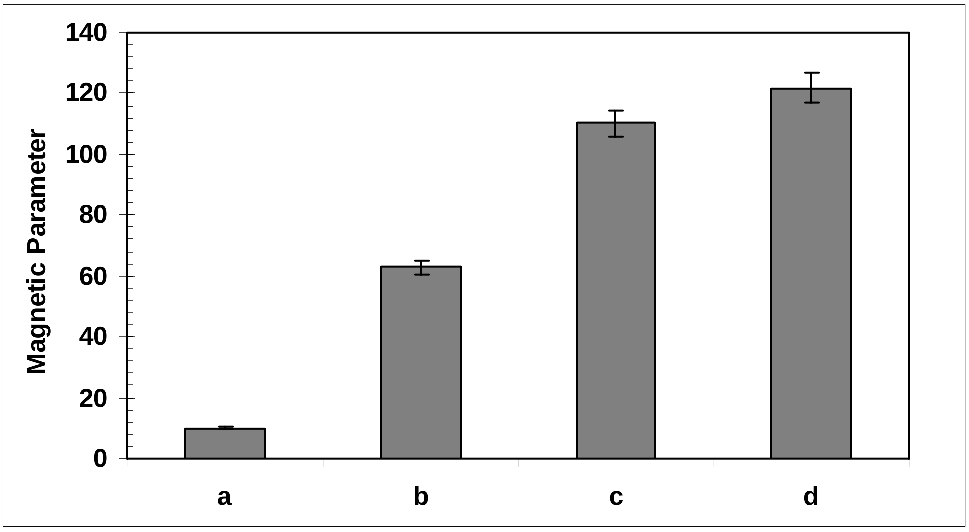



**Figure 2.** Magnetic Parameter Values of the Microstructures
(a: Martensite; b: Tempered Martensite, c: Fine Pearlite-Ferrite; d: Coarse Pearlite-Ferrite)

The graph of relative r.m.s. voltage versus relative magnetic excitation field show clear differences among microstructures (Figure 3). The peak position shifts to the lower values of magnetic field in the order of tempered martensite, fine pearlite-ferrite, and coarse pearlite-ferrite. In parallel to the softening of the microstructure, the low amplitude broad peak of as-quenched martensite transforms into high amplitude narrow peaks situated at lower magnetic field for the other phases.

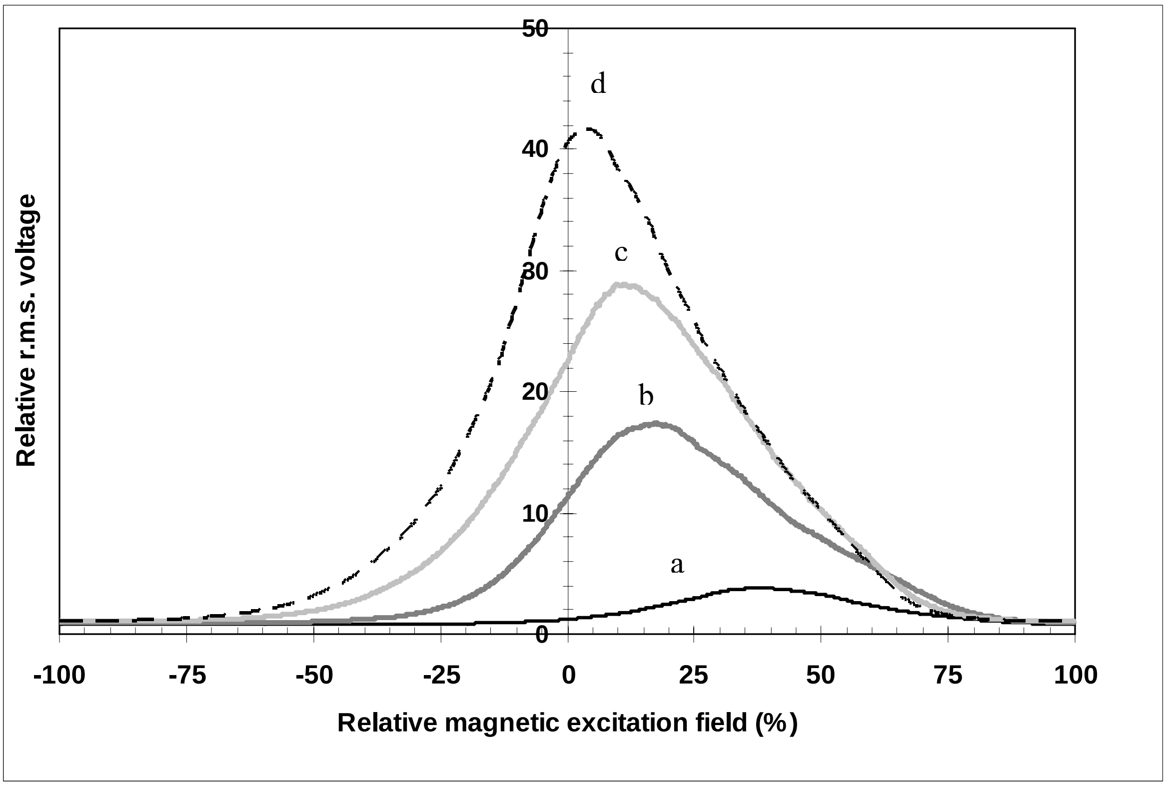



**Figure 3.** Relative r.m.s. Voltage versus Relative Magnetic Excitation Field Graphs for the Microstructures
(a: Martensite; b: Tempered Martensite, c: Fine Pearlite-Ferrite; d: Coarse Pearlite-Ferrite)

Average size of the domains is very small in the quenched specimen due to small martensite needles. Besides, pinning of the domain walls due to high dislocation density in the martensite laths increases the resistance to domain growth. The reversal of magnetisation requires a strong field, displacements of the domain walls are short, and it is difficult to create new walls. Therefore, the resulting MBN peak is very weak and situates at a higher magnetic field.

After 600$^{o}$C-tempering of the quenched sample, the needle-like martensite transformed to a structure consisting of spheroidal cementite particles in the ferrite matrix, and residual stresses are almost completely relieved. In parallel to the morphological change in the microstructure, the magnetic structure becomes coarser, and the average size of domain walls increases. Since the resistance to the nucleation and motion of the domain walls decreases the MBN signal amplitude increases remarkably, and the signal peak is situated at lower values of the magnetic field strength.

The microstructures consisting of ferrite grains surrounding pearlite colonies give the highest amplitude for the MBN peak. High MP values indicate that there is a wider range of jump sizes in the pearlitic-ferritic samples than those in the samples containing martensite and tempered martensite. The maximum size of domain wall jump for ferrite is dependent upon the average size of ferrite grains because grain boundaries act as an effective pinning site. Pearlitic structure consists of ferrite and cementite lamellae that formed along certain crystallographic directions within prior austenite grain. Under the effect of a magnetic field, the preferential orientation between lamellar colonies may facilitate passage of a domain wall across the colony interface, leading to very large domain wall mean free path under favourable conditions.

The amplitude of the MBN signal of the coarse pearlite-ferrite is higher than that of the fine pearlite-ferrite, and there is a remarkable difference in the MBN fingerprints (Fig.3-c and 3-d). Coarsening of the pearlitic-ferritic microstructure results in a further increase in the amplitude of the MBN peak, i.e., there is significant change in the jump size. The excitation field strength required for the movement of domain walls from pinning sites, i.e., interfaces between ferrite and pearlite regions, and those between ferrite and cementite layers, decreases remarkably.

### *3.3 Ultrasonic Measurements*

As seen in Figure 4, the microstructure having the lowest sound velocity is martensite, which is the phase having maximum randomness and dislocation density. During quenching each austenite grain suddenly transforms to long and thin laths of martensite by diffusionless lattice shear, which results in a high amount of lattice distortion and elastic anisotropy in the prior austenite grain volume.

Formation of carbide particles and reduction of dislocation density resulted in a less distorted lattice after tempering at 600°C, and therefore, a higher sound velocity than that of the as-quenched structure. Due to the inverse relation between velocity and density, the increase in the sound velocity is due to increasing elastic modulus rather than increasing density. These results are in agreement with those of the previous studies [15,16].

In the isothermally treated samples, the main difference is the spacing of the ferrite-cementite lamellae, and volume fraction and size of the ferrite (Figure 1-c and 1-d). The sound velocity of coarse pearlite-ferrite is higher than that of fine pearlite-ferrite because the content and size of ferrite in fine pearlite-ferrite is lower and the lamellea spacing is shorter than the coarser one [13].

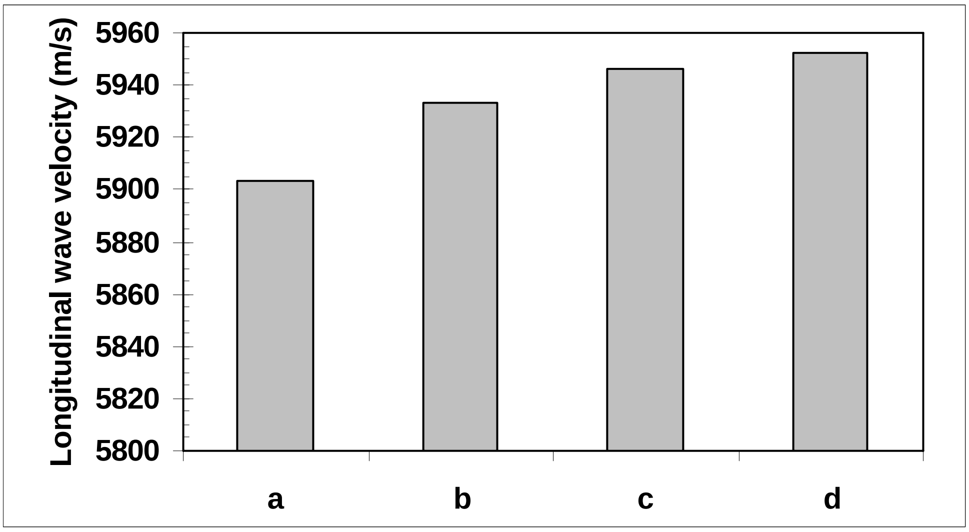



**Figure 4.** Longitudinal Wave Velocities of the Microstructures
(a: Martensite; b: Tempered Martensite, c: Fine Pearlite-Ferrite; d: Coarse Pearlite-Ferrite)

### *3.4 Comparison of the Results*

Longitudinal waves give information about the volume that is the average along the travel path of the sound beam whereas MBN signal contains information from a small volume near the surface whose depth is dependent upon the excitation frequency of the external magnetic field. In this study, it is possible to compare sound velocity and magnetic parameters because the aimed microstructures exist uniformly in all specimens.

The results show the similar tendency: martensite has the lowest MBN response and the lowest sound velocity, and these values increase in the following sequence: tempered martensite, fine pearlite-ferrite, and coarse pearlite-ferrite. However, the magnetic parameters are much more sensitive to the variations in the microstructure. Sound velocity increased from 5902 m/s (martensite) up to 5950 m/s (coarse pearlite-ferrite) whereas MP value changed from 10 mV (martensite) up to 120 mV (coarse pearlite-ferrite). These values correspond to approximately 1 % increase in the sound velocity and 1100 % increase in the MP value.

The ultrasonic pulse-echo method requires a sample with parallel surfaces, and sensitive measurement set-up; which is rather difficult in the industrial applications.

The raw magnetic noise data contain a series of voltage pulses, and associated magnetic field values. Various parameters can be used to evaluate these signals such as r.m.s. of the noise, analysis of the noise frequency, the number of pulses versus applied field, the maximum pulse size, r.m.s. pulse size, etc. This makes the comparison of the results of different studies difficult because the same quantities are not always measured. Moreover, some discrepancies, such as observation of variations in the number and shape of MBN peaks reported in different studies on similar materials, possibly caused by inconsistencies in experimental set-up and conditions. Another problem is the risk of mixing the effects of microstructure and residual stress state. Therefore, it is necessary to adopt a standard set of experimental practices or to conduct systematic studies before using MBN method for microstructure characterisation in industrial applications.

## 5 Conclusion

SAE 4140 specimens consisting of martensite, tempered martensite, fine pearlite-ferrite, and coarse pearlite-ferrite were investigated by Barkhausen noise and sound velocity measurements. Applying the same austenitisation procedure, the influence of microstructural non-uniformity and austenitic grain size were eliminated.

For the as-quenched state the MBN signal is very weak, and situated at high magnetic field since the domain walls are pinned as the result of high dislocation density and small martensite needles. MBN peak amplitude remarkably increases, and the peak position shifts to the lower values of the magnetic field of excitation after tempering at 600$^{o}$C due to the reduction of dislocation density, spherodisation and growth of cementite precipitates in the ferrite matrix. MBN peak goes to a maximum, and the peak position shifts to very low excitation field values in the pearlitic-ferritic samples due to the coarser and softer microstructure that requires less magnetic energy for domain movement.

Similarly, the lowest sound velocity belongs to the as-quenched specimen due to high amount of lattice distortion and elastic anisotropy caused by austenite-to-martensite transformation. 600$^{o}$C-tempering reduced the dislocation density and lattice distortion, and therefore, caused an increase in the sound velocity. Isothermal treatments resulting in pearlitic-ferritic microstructures increased the sound velocity further since the lattice distortion and misorientation is less. Sound velocity of fine pearlite-ferrite have been found lower than that of coarse pearlite-ferrite since the content and size of ferrite in fine pearlite-ferrite is low and the lamellea spacing is short compared to the coarser one.

It has been concluded that MBN parameters are more sensitive to the microstructural variations in steels than the sound velocity. Once the quantitative relationships between magnetic and microstructure parameters are established, MBN method can be used efficiently and effectively for evaluating the microstructural state of the ferromagnetic steel components during the fabrication or service.

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