Characterization of inhomogeneity in microstructure at the surface layers of gear steels by Magnetic Barkhausen Noise

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Article information	Abstract
Key words *magnetic Barkhausen Noise (MBN), carburization, decarburization, inhomogeneity, ferrite, martensite* *Received 26 September 2022, Accepted 12 October 2022, Available online 13 October 2022*	*The effect of gradients in hardness, microstructure and composition in the surface layers on magnetic Barkhausen noise (MBN) was investigated in two widely used gear steels. In the experiment one material was through hardened in two ways: (i) A set of Ovako 667 was hardened according to the standard process of this type and, (ii) Another set was deliberately decarburized. The other material, EN36 was gas case carburized according to the standard procedure. It was found that, the inhomogeneity in the decarburized and the case-carburized materials showed up clearly in the MBN measurements. This took the form of a two-peak MBN profiles whereas, a single peak profile was seen with the homogenous martensitic microstructure specimen. It is found that the shape of the MBN profile is significantly affected when a gradient in microstructure is induced by a gradient in carbon content. This was confirmed by metallographic examination and the microhardness tests. The result concludes that the MBN as an effective non-destructive testing technique which may replace the used destructive techniques..*

I. INTRODUCTION

When a ferromagnetic material is magnetized by a varying magnetic field, local changes in the magnetization induce voltage pulses in a search coil. This phenomenon is referred to as magnetic Barkhausen noise (MBN). It is principally associated with the irreversible movement of domain walls and discontinuous changes in the magnetization rate that result when domain walls overcome obstacles such as grain boundaries and precipitates [1]. Recently, attention has focused on the shape of the MBN profile, in which the intensity of Barkhausen noise is viewed as a function of the applied current. Measurement of the MBN profile opens the possibility of detecting differences in materials that might not be revealed using a single parameter such as the root mean square value. In particular, the MBN profile might be used to reveal gradients in structure and composition that occur in case carburized steel or in components with a decarburized surface layer [2].

Carburization is widely used for case hardening steel to produce enough hardness at the surface of eutectoid composition and a suitable toughness at the subsurface of low carbon content. Here, the gradient in carbon content produces a gradient in microstructure and hardness at the subsurface. Through hardening by quenching in air as with Ovako 667 is also widely used in engineering applications nowadays. Here, the variation in hardness is produced by the variation in microstructure with no change in composition. Because of the technical requirements of the two processes, the compositions of the alloy steels used in the two processes are different. Since the eutectoid composition of Ovako 667, the austentising process need to be carried out in vacuum to avoid carbon loss and hence hardness degradation. It was the object of the present work to investigate the ideally through hardened specimen and a decarburized one of Ovako 667 steel. Also, to compare that result with the MBN responses of commercial case-carburized with the aim of seeing if the presence of composition gradient at the surface layers is indicated by the profile shape change.

I. MATERIALS AND METHOD

The experiment was planned to test the idea of the effect of carbon gradient on magnetic Barkhausen noise profile at the surface and the subsurface layers of the most widely used spur gear steels. Consequently, two types of steel used in gear manufacturing and usually hardened by different mechanisms were used in this comparative study: -

1- The case-carburizing steel EN36 (AISI/SAE 3412)

2- The fully hardened by air-cooling from the austenite region Ovako 667 steel.

The initial chemical compositions of the base stock of the two kinds of steel are shown in Table 1. The case-carburizing steel EN 36 is used commercially for gears and other components that require high wear resistance. In the present work, bars (10×10×120 mm) machined from the stock to be heat treated in different conditions to give the planned microstructures.

Through hardening produces the desired hardness by heating to the austenite region and rapidly cooling in air. The chemical composition remains unchanged in the process. In carburization, a hardened case is obtained by diffusion of carbon into the material from the surface, followed by appropriate heat treatment.

(i) Gas carburization was carried out at 935 o C with the aim of achieving a case depth of about 1mm.The target carbon content was 0.72% at the surface, falling to 0.14% in the core. After carburizing, specimens were reheated to 820 o C and soaked for 2h before oil quenching. Specimens were tempered at 175 o C for 2h after quenching. The composition of both steels before heat treatment is given in Table 1.

(ii) One set of Ovako 667 specimens was hardened in a proper way in a vacuum furnace at 870o C to produce martensitic structure throughout the specimens. The other set of Ovako 667 was deliberately austenitised in a muffle furnace in air at 950o C for 60 minutes before air cooling. This treatment produced specimens with decarburized layer through the surface.

TABLE I. COMPOSITION (WT%) OF THE EN36 STEEL USED IN THIS STUDY, (BALANCE FE).

	EN 36	Ovako 667
C	0.14	0.67
Mn	0.5	1.48
Ni	3.31	0.11
Cr	0.9	1.03
Mo	0.11	0.25
Si	0.27	1.46
P	0.005	0.007
S	0.014	0.16

In order to proceed in the experiment, microhardness profiles were taken from the metallographic section from three sets of specimens. For the EN 36, the case depth was identified by microhardness profile and was found to be about 1mm at a hardness of 550 HV as shown in Fig. 1.

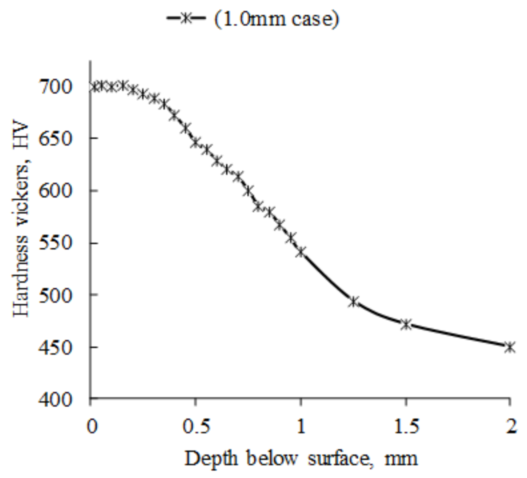

Figure 1. Figure 1. Microhardness of carburized specimen

Optical micrographs of the case carburized EN 36 surface and the bulk material are shown in Fig. 2

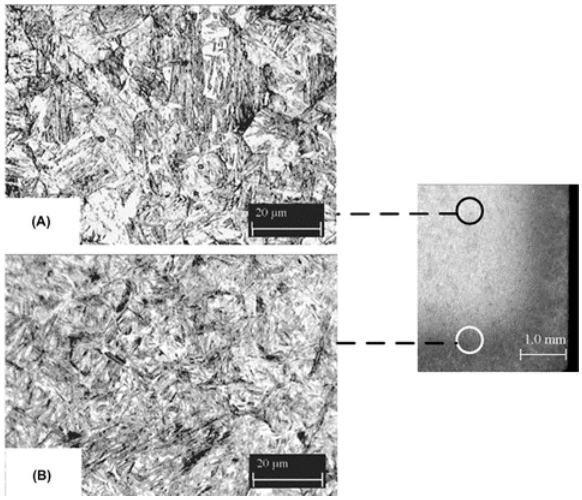

Figure 2. Microstructure of carburized EN36, The bulk material (A). The case (B)

Microhardness profiles of the two sets of Ovako specimens were produced as shown in Fig, 3. The microhardness profiles show the status of the produced microstructure throughout the cross section. The properly hardened set showed almost constant hardness values of about 730 HV (characteristic of Martensite), whereas the decarburized one showed gradient in the values at the surface and the subsurface areas. Decarburization produced ferritic microstructure at the surface with a hardness of about 200 HV (characteristic of ferrite), whereas the hardness the martensite bulk was found similar to properly hardened one. The gradual increase of hardness was attributed to the change of microstructure depending on carbon content (ferrite at the surface followed by hypo-eutectoid, towards eutectoid structure at the bulk)

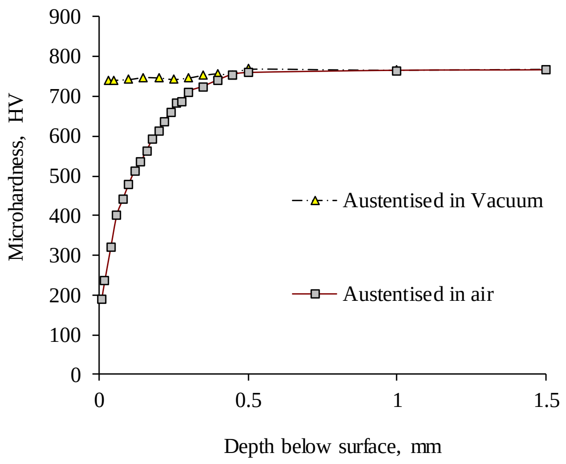

Figure 1 Ovako 667 Microhardness of 2 austentising times

A martensitic structure in the bulk can be seen with ferritic structure at the surface. The ferrite microstructure can be seen at the surface and martensite microstructure in the bulk as shown in Fig. 4

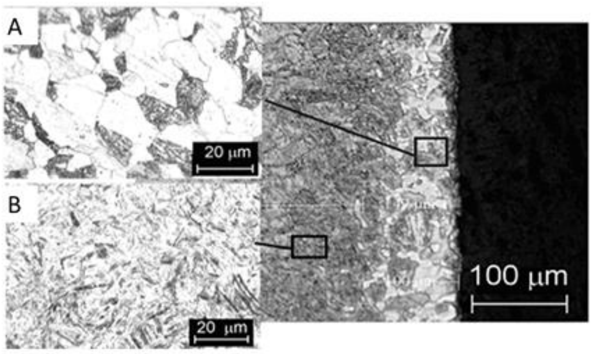

Figure 2. Effect of decarburization on the microstructure of quenched Ovako 667 specimen. The ferrite microstructure can be at the surface (A) and martensite microstructure in the bulk (B).

The MBN measurements were made using equipment developed in the author's laboratory. The testing procedure was developed to give a high degree of reproducibility, i.e. to produce minimum variations in a run of tests on the same specimen. A schematic illustration of the equipment is shown in Fig. 5. To produce a constant rate of magnetic induction in the specimen, the U-shape electromagnetic yoke is fed by a triangular waveform from a bipolar amplifier to take the specimen to near saturation at maximum current. The amplitude of the driving current to produce a maximum magnetic field strength of 4.5 kA m-1 at a frequency of 1 Hz was 1 A. A relatively low excitation frequency was used to minimize eddy current opposition to the applied magnetic field and to ensure a relatively slow magnetization rate in the sample.

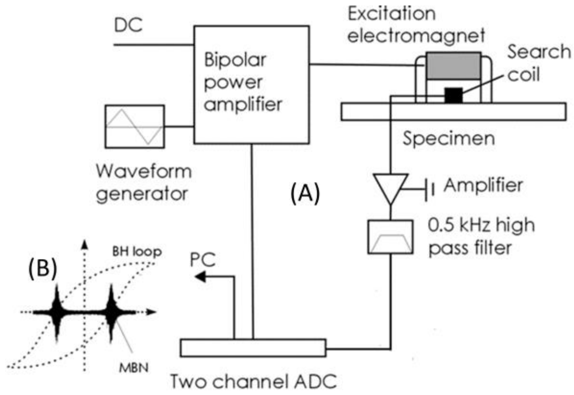

Figure 3 Schematic layout of the MBN measurement apparatus

The data was processed using a Matlab script to generate a profile characteristic of the profile of the output emf of the search coil. The signal (Fig. 5(B)) was rectified and the root mean square voltage was calculated using a running average of 15 points. As appropriate for the skin depth relationship with the excitation frequency (1 Hz) and the analyzing frequency range (3–100kHz), the broadband MBN signal containing multiple frequencies samples the specimen to the maximum depth. An important requirement in the MBN measurements was to produce data that was reproducible across a large number of magnetic cycles and was insensitive to any variations in the location of the energizing electromagnet and search coil. This is important because the magnetizing yoke and search coil were demounted at each step during material removal, as described below. Very good reproducibility was achieved in this experiment.

II. RESULTS AND DISCUSSION

To a first approximation, the intensity of MNB emission is proportional to the differential permeability of the material, i.e. proportional to the instantaneous slope of the BH curve [3]. Thus, the profile of MBN emission is anticipated to peak at a positive field with increasing current and peak again at a negative field with decreasing current as the state of magnetization of the sample moves around the BH loop. The two profiles should be mirror images reflected about the H = 0 axis (Fig. 5 (B)). This was observed in the experiments, but only the profiles obtained with a rising current are shown in the results in Figs. 6 and 7.

A- *Case carburized EN 36 steel*

It was noticed that for specimens of case depth less than or equal to 1 mm, MBN profiles showed two overlapping peaks. MBN activities detected by the search coil, from lower carbon content in the subsurface and higher carbon content at the near surface areas. The first peak at lower field may be attributed to the average domain walls activities at lower energy pinning sites (lower carbon content) martensitic structure at the sub-surface. The other peak at higher field may be attributed to the average domain walls activities overcoming barriers at higher carbon content regions near the surface.

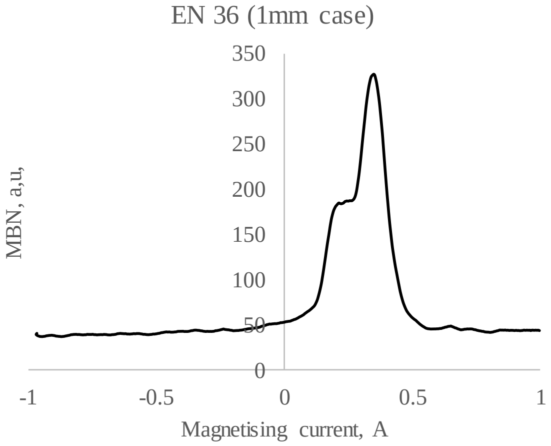

Figure 4. MBN profile from the carburised specimen

B- Ovako 667

Ovako (667) steel specimens were decarburized deliberately in air in the austenite region for 60 minutes prior to quenching. This produced a martensitic structure with Vickers hardness of about 730 HV in the bulk of the material and a decarburized layer of ferrite hardness was found to be about 300 HV at the surface. Two specimens were heat treated in this way but each was held in muffle furnace in air at 950□C for 60 minutes before air cooling. This treatment produced specimens with decarburized layers (Figs.3, 4).

The MBN profile from the specimen austenitised in vacuum showed a single peak at a high field, which was characteristic of the magnetically hard martensite. The specimen oxidized for 60 minutes, which had the decarburized surface layer, showed another peak closer to zero current (Fig. 7). It seemed reasonable to assume that this profile strongly reflected the characteristics of the decarburized layer.

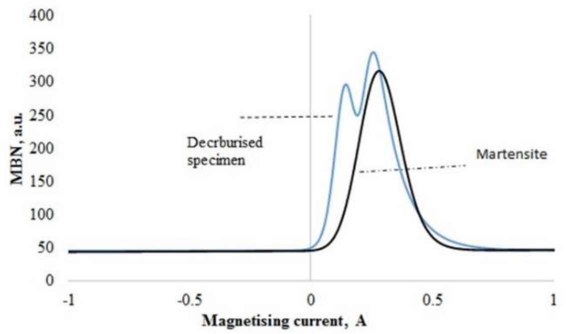

Figure 5. Ovako 677 MBN profiles, A- homogenous martensitic microstructure and (B) the hardened-decarburised condition.

The case carburised and decarburised materials have two distinctive microstructures broadly, the bulk and the surface. The associated magnetic microstructures are also different and hence, their response under the applied field are independent. It is well known that each ferromagnetic metallurgical state has a particular Barkhausen noise activity based on the fact that MBN peak value is directly proportional with hardness [4,5].

There are two MBN bursts in each magnetic cycle. After averaging the MBN burst, peaks will occur approximately at the coercive points (B = 0) [6]. Thus, any change in the B-H loop induced by microstructural change will be reflected in the MBN profile. If the loop becomes narrow (Fig. 8 (a)) with a steeper maximum slope, the peak MBN emission increases and the peak position moves towards H = 0. Conversely, if the loop becomes broader with a smaller maximum slope, the peak is reduced and its position moves away from H = 0 (Fig. 8 (b)). It follows that we expect a magnetically soft material to have a large MBN peak occurring at a small energising current. A magnetically hard material should have a smaller MBN peak occurring at a larger energising current.

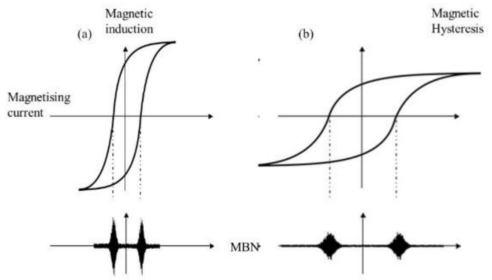

Figure 6 Illustration of the relation between the shape of the B-H hysteresis loop and the MBN peaks height and peaks position. In the theory [3], the intensity of emission is proportional to the slope of the hysteresis curve.

III. Conclusion

1. The though hardened in vacuum specimen showed a single peak at high magnetic field which is an indication of martensite. The destructive tests performed to the specimen showed a homogenous microstructure of martensite with no indication of carbon loss at the surface.
2. Results for the decarburised and the case-carburised steel show evidence of two overlapping peaks in the MBN profiles as a function of the applied field. The microstructural variations in the decarburised and carburised steel were also investigated by destructive tests and showed two major microstructural constituents as an indication of different carbon content.
3. Barkhausen noise technique was found sensitive be used to differentiate the two metallurgical states for the surface and for the bulk. changes. Soft magnetic microstructure was indicated by a peak at low field and the magnetically hard specimen was indicated by a peak at higher field.

References

[1] M. Vashista, and Moorthy, V., "On the shape of the magnetic Barkhausen noise profile for better revelation of the effect of microstructures on the magnetisation process in ferritic steels". *J. Magn. Mater*., Vol. 393, pp. 584-592, 2015.

[2] D. Kukla, L. Piotrowski and M. Szwed, "Evaluation of hardness layers carburised and induction hardened AMS 6414 steel using magnetic non-destructive techniques". *Weld Techn. Rev*., Vol. 88, pp. 46- 50, 2016.

[3] D. C. Jiles, "Dynamics of domain magnetisation and the Barkhausen effect" *Czech. J. Phys*., Vol. 50, pp 893-924, 2000.

[4] C. Somrerk, H. Wanlop, and J. Pitthaya, "Development of Barkhausen Noise measuring system for evaluating steel properties: Hardness" *Key Eng. Mat*., Vol. 856, pp 152-159, 2020.

[5] O. Saquet, J. Chicois, A. Vincent, "Barkhausen noise from plain carbon steels: analysis of the influence of microstructure", *Mat. Sci. Eng. A*, Vol. 269, pp 73-82, 1999.

[6] D. Alexandro, J. Guunther, and F. Gerhardt, "Case depth in SAE steel using Barkhausen noise" *Mat. Res*., Vol. 16 (5), pp 1015-1019, 2013.