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Surface decarburisation of steel detected by magnetic barkhausen emission

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The effect of decarburisation of the surface layer on magnetic Barkhausen noise (MBN) emission was investigated in quenched and tempered steel containing 0.67% carbon. The MBN profile of intensity versus energising current from the un-decarburised material showed a single peak typifying the martensite structure. After decarburisation, a profile with a double peak was obtained. The presence of the decarburised layer produced a second, overlapping peak at a lower field value. The height of the second peak increased with increasing depth of decarburisation and its position moved to increasingly lower field values. © *2005 Springer Science + Business Media, Inc.*

1. Introduction

When ferromagnetic material is magnetised by a varying magnetic field, the local change in the magnetisation induces voltage changes in a search coil placed on the surface. Barkhausen noise is mainly associated with the irreversible domain wall movement and refers to the abrupt discontinues changes in the magnetisation rate that result from domain walls overcoming various types of obstacles in their path. Obstacles include grain boundaries, voids and precipitates [1]. Its sensitivity to microstructural inhomegeneities makes MBN potentially useful as a non-destructive testing technique.

Vaidyanathan *et al.* [2] investigated the possibility of measuring the case depth of an induction-hardened steel using MBN measurements. They concluded that the effective depth is reflected in the MBN profile is in the range below 0.7 mm by showing a small peak in a low field strength reflecting the core material (pearlite) and larger peak at higher field strength, indicating the martensitic layer. This is due to the microstructural change through the depth with the result that two major domain walls populations contribute to the magnetisation process independently. Bach *et al.* [3], using a different experimental arrangement, showed that a case depth of 5 mm could be detected in the MBN profile with double peaks. They used the ratio of peak heights as an indicator of the case depth. Dubois and Fiset [4] correlated case depth in case-carburised steel with the frequency spectrum of the MBE signal integrated over a range of frequencies specific to the steel type. Vaidyanathan *et al.* [5] used the MBN technique to evaluate the carburisation depth in ferritic steels. They showed that the variation of carbon content affects the magnetic properties and consequently the BN signal level. As the carbon content increases, the intensity of MBN emission was found to decrease.

If a carburised case can be detected using MBN measurements, it follows that it ought also to be possible to detect a decarburised surface layer. Decarburisation of steel during heat treatment is known to be deleterious to fatigue strength of the material and it would be useful to have a non-destructive test for its occurrence. However, the present authors are not aware of any published work on MBN and decarburisation. It is the object of the present paper to present results on MBN measurements made on steel specimens that were decarburised by austenitising in air for various times prior to quenching and tempering.

2. Method and materials

The steel used in the investigation has recently been developed for low cost manufacture of wear-resistant machine elements. The composition of the stock material is shown in Table I. Specimens were heat treated by austenitising at 950°C followed by air cooling. This produced a martensitic structure with Vickers hardness between 740 and 760 kgf mm^{-2} in the bulk of the material.

Six bars ($10 \times 20 \times 100$ mm) were heat treated in this way but each was held in air at 950°C for a different time before cooling in air. The oxide film produced at the surface was removed by light grinding after heat treatment. The range of times of exposure at 950°C produced specimens with decarburised layers of varying depths. An example is shown in Fig. 1. The martensitic structure of the bulk can be compared with the ferrite grains that can be seen in the decarburised surface layer. The effect of decarburisation is also revealed

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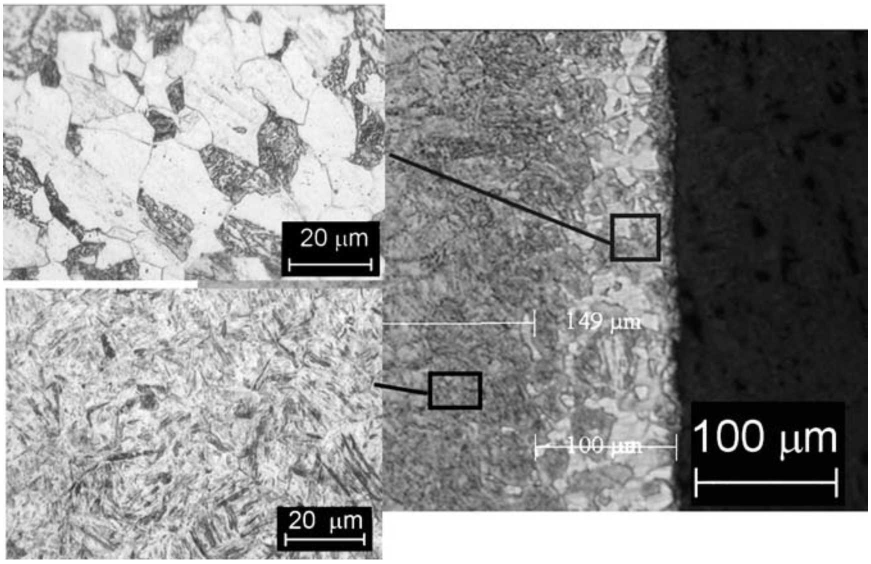

Figure 1 Decarburised layer showing martensitic and ferritic microstructures.

by the hardness profile in Fig. 2. Decarburisation produces a ferritic microstructure with a hardness between 190 and 210 kgf mm^{-2}, compared with a bulk hardness of 750 to 770 kgf mm^{-2}, characteristic of the martensite. The measured hardness profiles for the different specimens provide a means of characterising the extent of decarburisation. The mean hardness in the layer is taken to be $1/2(H_M + H_F)$ where H_M is the hardness of the bulk of the material and H_F is the hardness of the ferrite, i.e. the lowest hardness measured in the extensively decarburised specimens. The interpolated depth (Fig. 2) corresponding to the value $1/2(H_M + H_F)$ is taken to be the half depth d_H of the decarburised layer. The relation between time of oxidation and d_H is shown in Table II.

The MBN measurements were made using equipment developed in the authors' laboratory. The testing procedure was developed to give a high degree of reproducibility, i.e. to produce minimum variations in the results in a run of tests on the same specimen. A schematic illustration of the equipment is shown in Fig. 3. To produce a constant rate of 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 value of the driving current to produce a maximum magnetic field strength of 350 Gauss is ±1 A (±20 V) at a frequency of 0.2 Hz. A relatively low excitation frequency was used in the experiments to minimise eddy current opposition to the applied magnetic field and to ensure a relatively slow magnetisation rate in the sample.

Barkhausen emission is detected by an inductive search coil with 16000 turns wound around a ferrite core. The signal is amplified in two stages to a gain of 40 dB and then filtered using a 3 to 100 kHz band pass filter. After filtering, the signal is passed through an additional amplifier with a variable gain of up to 60 dB.

TABLE I Composition of Ovako 677 steel

Element	C	Mn	Ni	Cr	Mo	Si	S	P
Wt%	0.67	1.48	0.11	1.03	0.25	1.46	0.007	0.016

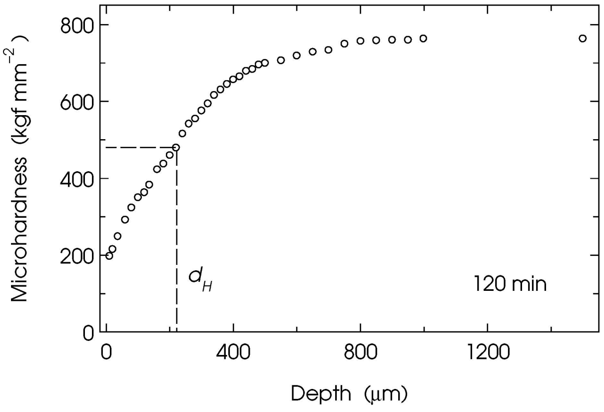

Figure 2 Hardness profile through decarburised layer showing definition of half depth d_H.

TABLE II Half depth d_H of decarburised layer as a function of time at 950°C

Time (min)	10	30	60	90	120	180
d_H (μm)	<30	30	88	112	222	287

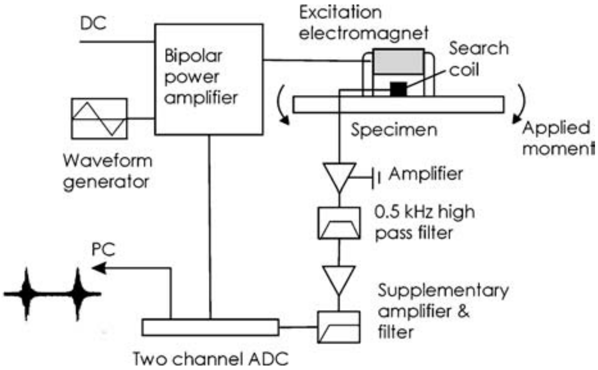

Figure 3 Schematic illustration of MBN apparatus.

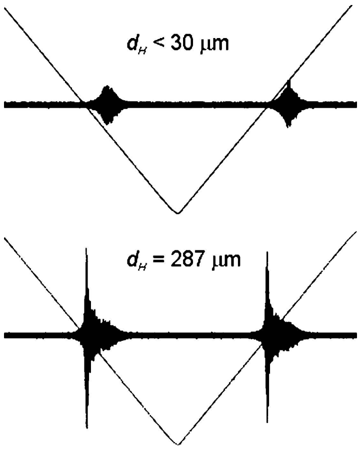

Figure 4 Examples of MBN emission following decarburisation: d_H is the half-depth of the decarburised layer. The triangular wave represents energising current.

To minimise interference, an additional 0.5 kHz high pass filter is used. The BN signal is then acquired using 20 Ms/s Pico Tech 12-bit DAC oscilloscope and stored in a PC. Examples of the emission recorded in this way are shown in Fig. 4. In classical models of the process, MNB emission is, to a first approximation, proportional to the differential permeability of the material. It follows that in a homogeneous material the emission is a maximum twice in each hysteresis loop. The intensity of the MBN emission is anticipated to peak at a positive field with increasing energising current and peak again at a negative field as the state of magnetisation of the sample moves around the BH loop. The two envelopes will be mirror images reflected about the H or current = 0 axis. This was observed in our experiments (Fig. 4), but only profiles obtained with a rising current are shown in the results below.

It is convenient to smooth emissions of the type shown in Fig. 4 to produce a measure of the amplitude of the envelope enclosing the signal. This was done using a Matlab script. The signal was rectified and the local root mean square voltage was calculated using a running average of fifteen points. Background noise was subtracted from the profile in the graphs shown in the next section.

As appropriate to the skin depth relationship with the excitation frequency (0.2 Hz) and the analysing frequency range (3–100 kHz), the broadband MBN signal containing multiple frequencies evaluates a volume of material with a depth of about 0.6 mm below surface.

3. Results and discussion

MBN profiles from specimens with various degrees of surface decarburisation are shown in Fig. 5a and b. The MBN emission profile from the sample oxidised for only 10 min (Fig. 5a) shows a single peak at a higher field, which is characteristic of the magnetically hard martensite. The specimen oxidised for 180 min, which has the largest decarburised surface layer, shows a pronounced peak at a position close to zero energising current with a broader tail at higher values. It is reasonable to suppose that this profile strongly reflects the characteristics of the decarburised material.

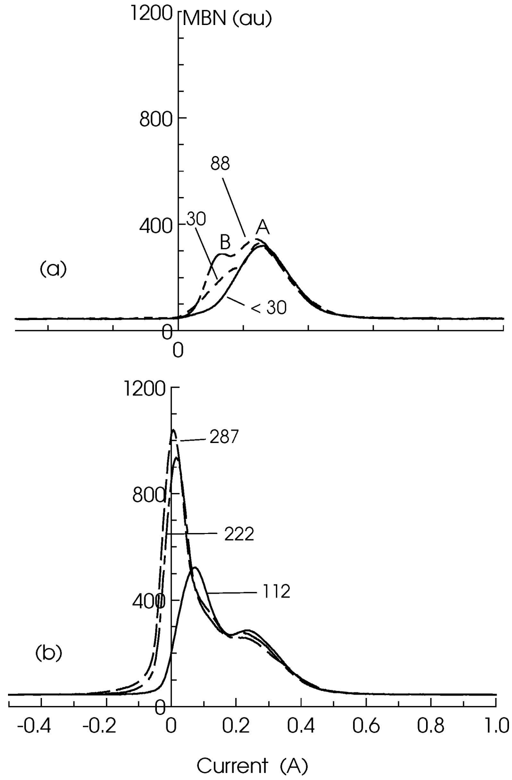

Figure 5 MBN profiles showing the effect of an increasing surface decarburisation. The numbers adjacent to the curves show values of the half depth d_H of the decarburised layer in micrometers.

Specimens that were oxidised for times between 10 and 180 min produced broad MBN profiles that appear to consist of at least two overlapping peaks (Fig. 5a and b). It seems reasonable to assume that the MBN profile reflects the gradient in carbon content and microstructure in the surface layer. For simplicity, we assume that profiles in Fig. 5 are generally composed of just two overlapping peaks. The peak at the higher field is associated with the martensitic structure and is labelled peak A. The peak at the lower field value is associated with the appearance of the ferritic structure and is labelled peak B. The effect of oxidation time on the heights of the two peaks is shown in Fig. 6. The height of the A peak declines slightly with increasing depth of the decarburised layer while the height of peak B increases sharply after oxidation for 50 min.

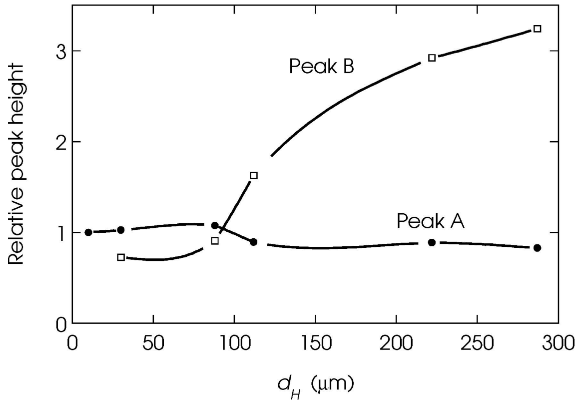

Figure 6 Relative heights of the MBN peaks A and B (Fig. 5) as a function of the half depth of the decarburised surface layer.

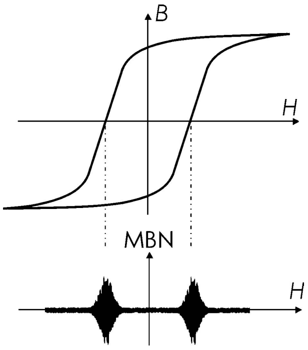

Figure 7 Schematic BH loop illustrating its relation to MBN emission.

Comparison of the profiles from specimens with the smallest and greatest depth of decarburisation shows that martensite produces a relatively small peak height, whilst ferrite produces much more emission at its peak. This is consistent with the fact that martensite contains heavily dislocated regions and twin boundaries that serve as additional barriers to magnetic domain wall movement. The position of the MBN peak is also sensitive to carbon content. As the carbon content decreases, the position of peak B moves to lower values of the applied magnetic field or energising current. According to the models of Sablik, Jiles and Augustyniak [7–9], peak MBN emission occurs approximately (but not exactly) at those points in the magnetisation cycle where the differential permeability (slope of the BH curve) is a maximum, as illustrated schematically in Fig. 7. If the BH loop narrows, the position of the MBN peaks will move to lower field values. The effect of removing carbon from steel is known to make the loop narrower. This is consistent with the results in Fig. 5, where the position of peak B moves to lower values of the energising current as the depth of the decarburised layer increases.

The above arguments give reasonable qualitative support to the idea that the broadened or two-peak MBN profile observed in the experiments derives from the gradient in carbon content and microstructure. This implies that the MBN emission at any energising current originates from material that has different BH behaviour at different depths. The details of this have not been investigated because of the complexity of determining the distribution of magnetic flux in an inhomogeneous material. Nevertheless, the present results indicate that the detection of multiple peaks and their comparison could provide a method for non-destructive testing of graded ferromagnetic alloys.

4. Conclusions

(i) The influence of inhomogeneity on magnetic Barkhausen noise profiles was investigated in low alloy steel (0.67% C) with a decarburised surface layer produced by oxidation during the course of heat treatment.

(ii) The decarburised samples show a broadened MBN profile containing at least two overlapping peaks. It is deduced that the inhomogeneity arising from the gradient in carbon content through the case is responsible for the distortion of the MBN profile.

(iii) The MBN peak associated with the martensitic structure is characterised by a lower peak height, occurring at higher field values. The MBN peak associated with the ferritic structure is characterised by a larger peak height, occurring at lower field values.

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