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Effect of Heat Treatment on Barkhausen Noise Behaviours of Deformed Low Carbon Steel

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Abstract. We investigated the Barkhausen noise profiles for the undeformed and deformed low carbon steel when the specimens were heat treated with modifications of microstructures of specimen: recovery, recrystallization process and stress relief. The Barkhausen noise parameter is almost constant in heat treatment at a lower temperature, while it shows a rapid decrease with heat treatment time at higher temperatures. The recovery process contributes to the decreases of Barkhausen noise signal in heat treatment at higher temperatures.

Keywords. Barkhausen noise, recovery, recrystallization, stress

1. Introduction

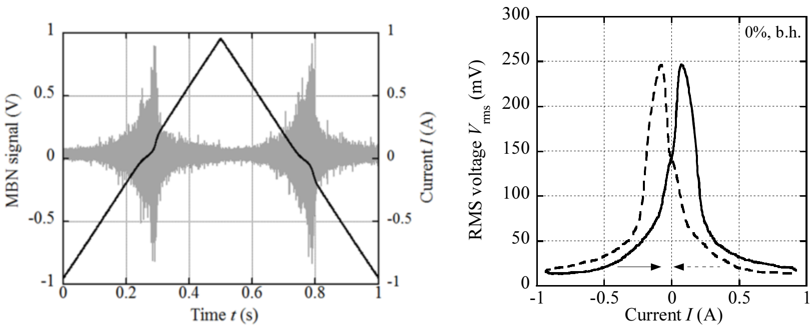
It is quite important to evaluate nondestructively degradation and residual stress of infrastructure construction such as bridges, expressways and turbine blades to maintain an integrity of constructions and a safety of human life. The degradation of constructions is based on microstructure changes of the steels composed the constructions. Almost steels show ferromagnetic properties and their magnetic properties depend strongly on microstructure changes, which means nondestructive evaluation (NDE) using magnetic measurement for degradation of infrastructure construction is possible [1]. One of effective NDE methods using magnetic measurement is Barkhausen noise (MBN) techniques [2, 3], because MBN is attributed to discontinuous domain wall movements. Domain wall movements depend on the magnetoelastic coupling between domain walls and microstructures. A lot of researches regarding the correlation between the magnetic properties including MBN properties and the mechanical characteristics during plastic deformation have been investigated [4] - [6]. There have also been a number of studies related to the correlation between magnetic properties and hardness when the grain size is altered [7] - [9]. In those researches, magnetic properties have good correlation with hardness. However, there are reports that the correlation between the magnetic properties and the mechanical characteristics is not simply when the steel that was plastically deformed has been heat treated [10], [11]. To enhance a reliability of the MBN method, investigation of the relationship between MBN properties and microstructures during heat treatment is required. Therefore, in this study, we evaluated MBN properties of deformed low carbon steel with cold rolling and investigated the effects of microstructure changes due to heat treatments on MBN profiles.

2. Experimental procedure

Low carbon steel (S15C) plates were prepared and one of those steels was undeformed and others were deformed by cold-rolling with reduction ratios of 5, 20 and 40%. The reduction ratio means the ratio of thickness of steel before and after cold-rolling. The composition of the steel is 0.16 wt.% C, 0.2 wt.% Si, 0.44 wt.% Mn, 0.019 wt.% P, 0.018 wt.% S, and 0.01 wt% Ni and Fe in balance. The plates were shaped into a disk of 24 mm diameter and 2 mm thickness by wire cutting. Those plates were heat treated in vacuum at 573, 773 and 873K (300, 500, 600°C) with heat treatment time from 0 to maximum 90 minutes for 773 and 873K and maximum 180 minutes for 573K followed by quenching in water. After heat treatment, the specimens were polished and then MBN properties of those specimens were measured using a magnetic yoke made of Fe-Si steel and an air-core coil. When measuring, a triangular current I of 1 Hz with an amplitude of 1A is applied to an excitation coil having 150 turns winding around the yoke for magnetizing a specimen, and an induced voltage at the air-core coil, 1000 turns and 64 mm^2 area and 4 mm height, made of Cu wire with 0.08 mm diameter, located at the surface of the specimen was captured by a PC after amplified by 1000 times and then filtered (100 – 200 kHz). Figure 1 (a) shows a typical example of measured MBN signal. The black solid line shows the applied current to excitation coil, and gray solid line is MBN raw signal. The rms value defined as the equation (1) is used for evaluation of MBN signal.

$$rms = \sqrt{\frac{1}{T}\int_0^T V_o^2 dt} \tag{1}$$

where V_o is the detected signal after amplified and filtered, and T is a half period of magnetizing field. Based on the results of MBN signal, MBN profile in which the moving averaged rms voltage, V_{rms} [12] are plotted against the current was obtained as shown in Figure 1 (b). The profile by the solid line is signal changes when the applied current changes from minus to plus and the dotted line shows the data when the current changes plus to minus. The MBN signal was subsequently evaluated by changing the direction of the magnetizing field. Here, the direction parallel to the direction of cold-rolling is defined as 0 degree, and then the measurements were done from 0 – 90°. We also evaluated the Vickers hardness of the specimens by a hardness meter with 300 g load.



(a) MBN profile against time (b) MBN profile against applied current

Figure 1 Time dependence of MBN signal and applied current to excitation coil (a). MBN signal changes against applied current to the excitation coil. (b.h. means "before heat treatment.")

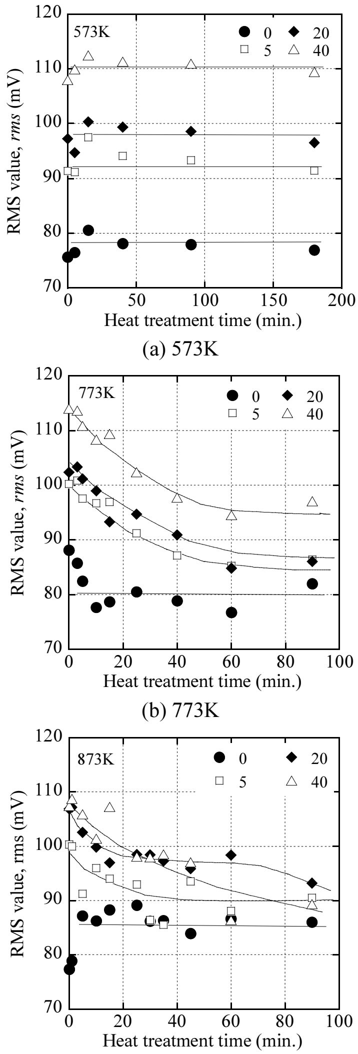


Figure 2 MBN signal dependence on heat treatment time for undeformed and deformed specimen with different heat treatment temperature.

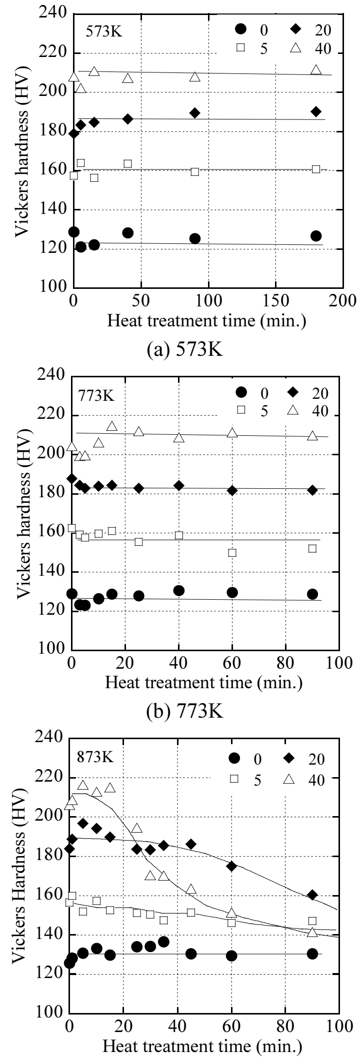


Figure 3 Vickers hardness dependence on heat treatment time for undeformed and deformed specimen with different heat treatment temperature.

3. Experiment results

3.1 Changes in rms voltage and Vickers hardness due to heat treatment

Figure 2 shows the dependence of rms voltage V_{rms} on the heat treatment time for the specimens with different reduction ratios at different heat treatment temperature. All measurements were done by magnetizing field applied parallel to rolling direction. Before heat treatment, the value of V_{rms} increases with increasing reduction ratio,

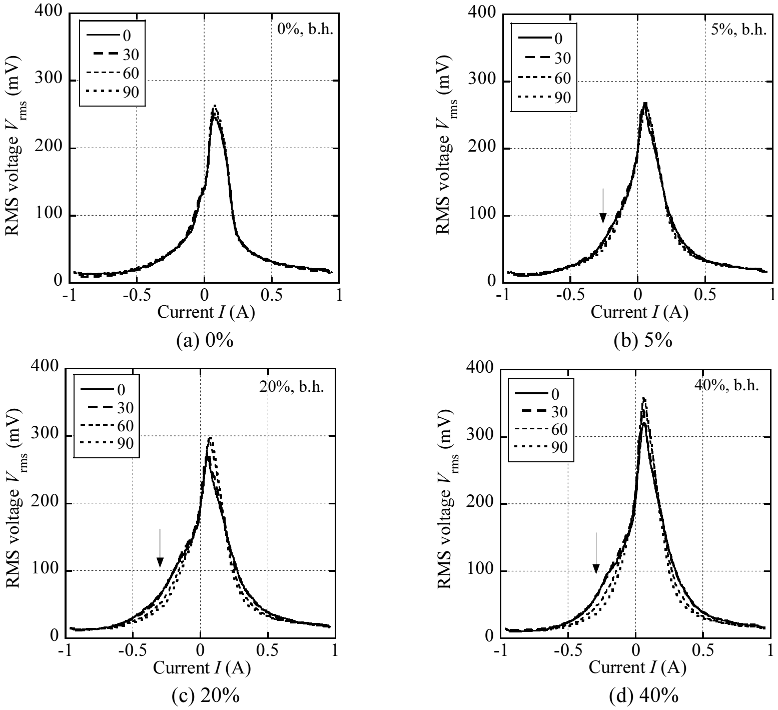


Figure 4 MBN profile measured with different applied field direction for undeformed and deformed specimens before heat treatment. (b. h. means "before heat treatment.")

which is explained by the increase of dislocations [13]. The value of V_{rms} is nearly constant for all specimens at 573K (300°C), while the value decreases with heat treatment time at 773K (500°C) and 873K (600°C) except undeformed specimens (0%). The reduction ratio of V_{rms} at 873K is larger than that at 773K, and the value becomes nearly constant at earlier heat treatment times.

Figure 3 shows the dependence of Vickers hardness on heat treatment time for the specimens with different reduction ratios at different heat treatment temperature. The Vickers hardness increase with increasing reduction ratio before heat treatment; this is caused by the increase of dislocations. The Vickers hardness is constant against heat treatment time for all specimens at 573 and 773K. On the other hand, there are changes at 873K, which depends on the reduction ratios. The specimen with a 40 % reduction shows rapid decreases around 20-25 minutes, then, continues to decrease gradually. The specimen with 20% shows the constant value up to 40 minutes, then decreases. 5% reduction slightly decreases and 0% shows no change.

3.2 MBN profiles and orientation dependence

Figure 4 shows the MBN profiles for the undeformd and deformed specimens with different magnetizing direction before heat treatment. All profiles for the undeformed specimen are same profile, whereas the MBN profiles show magnetic anisotropic properties for the deformed specimens; the profiles of all angles have a significant peak at I = 0 – 0.1 A, and that of 0 or 30° for undeformed specimen have a broad peak around I = –0.3A and the peak becomes prominent as the reduction ratio increases

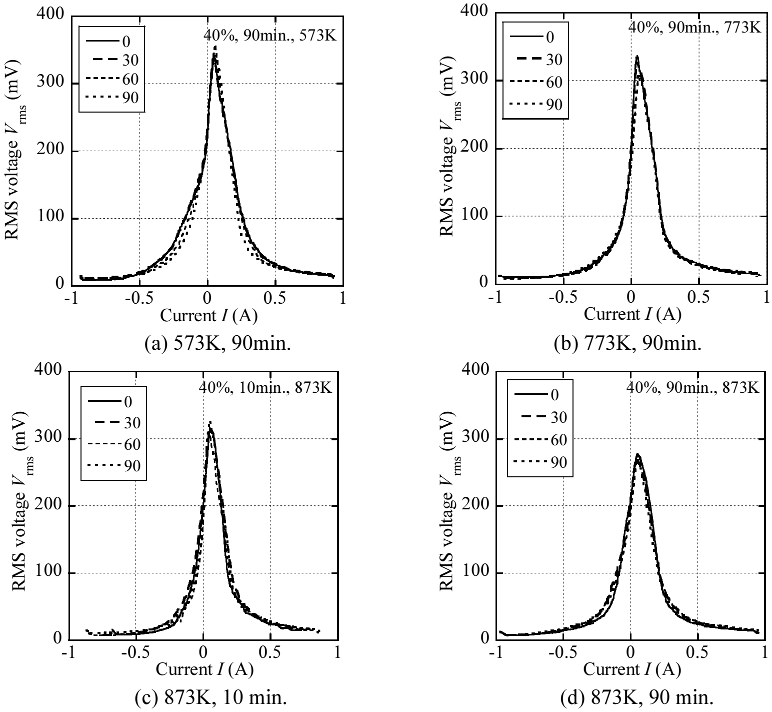


Figure 5 MBN profile measured with different applied field direction for undeformed and deformed specimens after heat treatment.

(indicated by arrow in Fig. 4 (b) – (d)). The difference in profiles between 0 and 90 degrees also becomes apparent with increasing reduction ratio. The peak height increases slightly with increasing reduction ratio.

Figure 5 shows the MBN profiles for the specimens with a reduction ratio of 40% with different direction after heat treatment at a different heat treatment temperature. Heat treatment time was 90 minutes for all temperatures and 10 minutes for only at 873K. We can see from Fig. 5 (a) that the MBN profile of the specimen heat treated at 573K has still magnetic anisotropy. The profiles show different aspects around $I = -0.3$ A; it depends on the magnetizing direction. On the other hand, when the specimen was heat treated at 773 and 873K, the broad peak disappears and the profiles show almost isotropic magnetically. As to the result with heat treatment at 873K, the anisotropic property already almost disappears at 10 minutes.

4. Discussion

According to our previous research, we confirmed that the dislocations increase homogeneously with increasing reduction ratios up to 10%. Then the dislocations tangle and form cell structures above 10%. The cell structures are elongated parallel to the rolling direction, which induces anisotropy of microstructures [12]. The number of pinning sites for domain wall increases with the increasing dislocation density, because dislocations act as pinning sites for domain wall motion; this contributes to the increase in MBN signal due to the increases in the number of MBN events. It is also known that the compressive stress remains along a rolling direction after cold-rolling [15] which can be attributed to the appearance of the broad peak on MBN profiles measured parallel to the rolling direction.

On the basis of microstructure observations using an electron backscatter diffraction (EBSD) and a transmission electron microscope (TEM), we confirmed the recrystallization occurs at 873K, and the recovery occurs at 773K and initial heat treatment stage at 873K [14]. The dislocations, pinning sites for domain walls, collapse and rearrange during the recovery process to reduce internal stress; this contributes to the decreases of MBN signal. The degree of release of internal stress depends on the heat treatment temperature; if the heat treatment temperature is high, its relaxation advance rapidly. Hence, the ratio of decrease in MBN signal becomes steeper with raising heat treatment temperature. Residual stress is also relieved by the heat treatment, which contributes to changes in the MBN signal as well. The cell structures were elongated to rolling direction before heat treatment, in one of the reasons why the MBN signal shows anisotropic, it transformed into isotropic sub-grains after heat treatment at 773K [14] which is attributed to the rearrangement of dislocations. These microstructures contribute to make MBN profiles become isotropic. On the other hand, recrystallization process produces new grain with the collapse of dislocation inside grain; however, this contribution to the MBN signal is not much in this study. Vickers hardness did not change at 573 and 773K, at which recovery process and stress relief occurs. Since hardness is the relative ease with which dislocations move, it may be affected mainly by the number of fixed dislocations. Only mobile dislocations collapse and rearrange during recovery process which causes the hardness to remain constant but reduce residual stress, related to internal stress caused by dislocation configurations, and MBN signal. On the other hand, all dislocations, both fixed and mobile, disappear during recrystallization, therefore the hardness starts to decrease. The MBN signal, however, does not show apparent change compared with hardness during recrystallization, which is attributed to the combined effect of a decrease in dislocations and an increase in the number of grains; decrease in dislocations induces reduction of MBN signal while small grains increase MBN signal. Additionally, MBN signal is more sensitive to internal stress than the number of pinning sites. The behaviour of hardness changes has no simple relation to MBN signal during heat treatment, which is different from the case in the cold-rolling process; there is good correlation between MBN signal and hardness.

5. Conclusions

The MBN signal of cold rolled low carbon steel was evaluated with heat treatment. The recovery process progresses at low temperature heat treatment (less than 773K here), this reduces the MBN signal and makes it have isotropic properties, although MBN signal shows anisotropic before heat treatment. These changes were brought through a reduction of internal stresses induced by an alteration of the dislocation morphology. However, these microstructure changes do not contribute to the hardness changes. On the other hand, MBN signal changes are not apparent during recrystallization whereas hardness is reduced by a dissipation of dislocations.

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