Magnetoacoustic Emission Characteristics on Cold Rolled Low Carbon Steel

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Abstract. This paper describes the behaviours of magnetoacoustic emission (MAE) of cold rolled low carbon steel specimens. The MAE rms voltage and the moving average analysis were used for evaluating the profiles of MAE signals. The MAE rms voltage and the peak value of averaged rms voltage rise rapidly with increasing cold rolling below 10% reduction ratio, and then they decreases at higher reduction ratio, whereas the magnetizing current when the averaged rms voltage takes a peak decreases up to 10% reduction ratio, then becomes constant value. As a result of the observation of microstructures by transmission electron microscopy, the dislocations increases homogeneously up to 10% reduction ratio, and then forms cell structures without a significant increase in dislocation density. The behaviours of MAE are attributed to the combined effects of cell texture and dislocation density.

1. Introduction
Magnetic Barkhausen noise (MBN) occurs when mainly 180° domain walls are unpinned from microstructural obstructions such as grain boundaries, inclusions and dislocations in a ferromagnetic material. Therefore MBN has interactions with microstructures of the materials. There are many investigations concerning MBN changes under various conditions including fatigue [1], irradiation [2], residual stress [3], creep [4], grain size [5, 6], etc. Since mechanical properties of a material also strongly depend on microstructures, those properties have good correlation with magnetic properties [7]. Consequently, MBN has been widely used as a tool for a characterization or a nondestructive evaluation (NDE) of ferromagnetic structural steels. On the other hand, magnetoacoustic emission (MAE) includes acoustic pulses generated by discontinuous motions of non-180° domain walls and localized strains. Because discontinuous domain wall motions arise from an interaction between domain walls and microstructures involving dislocations, grain boundary, etc., MAE is also a useful candidate for NDE technique for a degradation of mechanical properties and a characterization of microstructures. In addition, since MAE propagates through whole specimen unimpeded by eddy currents, MAE has an advantage over MBN technique. However, there are few researches that MAE characteristics are explained related to the microstructure changes observed experimentally [8, 9]. In this work, MAE of low carbon steel, typical structural steel, deformed by cold rolling was evaluated and its behaviour was discussed based on the observation of microstructure by transmission electron microscope (TEM).

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2. Experimental procedure

Low carbon steels (S15C) were prepared and annealed at 1173 K for one hour, followed by air-cooling. Then, those steels were cold rolled with different reduction ratios of 5, 10, 20 and 40 %. The chemical composition of the steels is 0.16 wt.% C, 0.2 wt.% Si, 0.44 wt.% Mn and Fe in balance. For measuring MAE, five kinds of plates (undeformed and cold rolled with 5 – 40 % reduction ratio) were ground into a dimension of $40 \times 60 \times 10$ mm$^3$.

The plate specimens were magnetized parallel to the rolling direction by a triangle current of 1 Hz and 1A amplitude using a single-yoke. The yoke was composed of a U-shaped Fe-Si yoke and a magnetizing coil as shown in figure 1. The dimension of the yoke is also shown in figure 1. The number of the magnetizing coil is 1000 turns. The MAE signals were detected by an acoustic emission (AE) sensor, i.e., a PZT (lead zirconate titanate) transducer (NF 903N) with a diameter of 3 mm, attached on a surface of specimen with a medium for good contact between the PZT sensor and the specimen. The resonance frequency of the PZT sensor is 350 kHz. The measurement system for MAE signals is illustrated in figure 2. The original MAE signals induced at the PZT sensor were amplified (60 dB), band pass filtered (300 – 400 kHz), and finally acquired with a sampling rate of 100 kHz. The MAE signals of each specimen were measured several times and averaged. The dependence of rms (root mean square) voltage on reduction ratio was studied. The rms voltage $RMS_{MAE}$ is defined as equation (1).

$$RMS_{MAE} = \sqrt{\frac{1}{T} \int_0^T V_{MAE}^2 dt}$$

where $V_{MAE}$ is MAE signals acquired and $T$ is a half period of excitation field.

In addition, rms voltage calculated with a moving average method [10] was adopted as an evaluated parameter in order to acquire much information. The data from each run consisted of a set of points $(t_n, I_n, V_n)$, where $t_n$ is the time at point $n$, $I_n$ is the magnetizing current at point $n$, $V_n$ is the value of $V_{MAE}$ at point $n$. Since sampling frequency is 100 kHz in this study, the index $n$ runs from 1 to $1 \times 10^5$ during 1 cycle. The data were divided into $n/m$ sample sets in each of which $V_n$ data of $m$ points are stored consequently. Here, $m$ is 50. For each sample set, rms voltage and averaged magnetizing current were computed as follows.

$$V_{rms} = \sqrt{\frac{1}{m} \sum_{i=1}^{m} V_i^2}$$

$$I_a = \frac{1}{m} \sum_{i=1}^{m} I_i$$

According to the calculation by equations (2) and (3), new data set $(t_j, I_j, V_j)$ was obtained and the

![Figure 1. Dimension of single-yoke.](image1)

![Figure 2. Measurement system for MAE.](image2)
index $j$ runs from 1 to $n/m$ (= 2000). For the data set $(t_j, I_j, V_j)$, moving average of rms voltage for $k$ sample sets was calculated using the following equation.

$$
V_{r.m.s.\_ave}^j = \frac{1}{k} \sum_{q=1}^{k} V_{j+q}
$$

When the index is $j$, the data sets $(i.e., V_j, V_{j+1}, ..., V_{j+k})$ were used for calculation of $j$th value of $V_{r.m.s.\_ave}$. Finally the data sets of $(I_\alpha, V_{r.m.s.\_ave})$ was obtained for each of $n/m$ points. Here, $k$ is 20.

To investigate the microstructures of the specimens, disk specimens of cold rolled steel were prepared and observed by TEM (Philips-tecnai 30).

3. Experimental results

Figure 3 shows a typical wave form of MAE signals and the magnetizing current applied to the magnetizing coil of the yoke against time for specimens undeformed (0 %) and deformed with 40 % reduction ratio. One cycle of MAE signal wave appears in a half cycle of the magnetizing current. The peak intensity of the MAE signal $V_{MAE}$ for 0 % is greater than that for 40 %. The rms voltage $RMS_{MAE}$ was calculated using equation (1) for each specimen based on the profiles shown in figure 3. Figure 4 shows the dependence of $RMS_{MAE}$ on the reduction ratio. The value of $RMS_{MAE}$ increases firstly and takes a maximum at 10 % followed by its reduction.
Figure 5 shows the changes of the moving averaged rms voltage \( V_{\text{rms, ave}} \) against the averaged magnetizing current \( I_a \) for a half cycle of magnetizing current. One can see an averaged rms voltage in each specimen has one peak and an intensity of magnetizing current at a peak for the undeformed specimen (0 %) is larger than that of deformed specimen. Figure 6 shows the dependence of the peak intensity in averaged rms voltage \( V_p \) and the magnetizing current at peak \( I_p \) on the reduction ratio. The peak \( V_p \) increases at first up to 10 % reduction ratio, and then decreases, while the magnetizing current at peak \( I_p \) decreases rapidly up to 10 %, and becomes nearly constant above 10 %.

Figure 7 shows the photographs of TEM observation for S15C steels [10]. For undeformed specimen, dislocations distributed homogeneously and a large amount of dislocations are generated with the increase in reduction ratio up to 10 %. Above 10 %, dislocations form tangles and then cell structures. The dislocation density estimated by the Ham method [11] is \( 5 \times 10^9 \) cm\(^{-2} \), \( 2 \times 10^{10} \) cm\(^{-2} \), and \( 6-10 \times 10^{10} \) cm\(^{-2} \) for 0, 5 and 10 % reduction ratio, respectively; for higher reduction, is not shown because of the formation of cell structures, which makes it difficult to estimate a reliable value of dislocation density.

4. Discussion

TEM observation shows that dislocations increase homogeneously firstly, and then tend to aggregate at the boundary of cell structure during cold rolling, and the dislocation density inside the cell texture is relatively low. These results show that dislocation density increases sharply during the reduction develops to 10 %, and then a higher reduction ratio does not induce a significant increase in dislocation density but induce only morphological changes in dislocations. As dislocations act as pinning sites for domain wall (DW) motion, the number of pinning sites for DW increases with the increasing dislocation density. When the number of pinning site increases, the event of MAE activity increases. Since the rms voltage \( RMS_{\text{MAE}} \) depends on the total event of MAE activity during one cycle of magnetization, \( RMS_{\text{MAE}} \) increases due to the increase in dislocation density up to 10 %. A large number of smaller cell structures may induce the reduction of the number of effective pinning sites for non-180° DW above 10 %; this causes the \( RMS_{\text{MAE}} \) decreases at higher reduction ratio.

The tendency in the peak of averaged rms voltage shows the same behaviour as the \( RMS_{\text{MAE}} \) values. However, below 10 % the parameter increases not remarkable as compared with \( RMS_{\text{MAE}} \) values, while the reduction above 10 % shows rapid decreases. These results may indicate that the number of pinning sites with weaker pinning forces increases with increasing dislocations up to 10 % reduction ratio. The magnetizing field at peak of the averaged rms voltage means a large number of MAE activity occurs at this magnetic field strength; many non-180° DWs were unpinned at these fields.
Since pinning sites with weaker pinning forces in creases, the magnetizing field at peak decreases below 10% reduction. Contrary, above 10 %, the forming of cell texture decreases the effective pinning sites, however, the pinning force does not change notably. Thus, only the peak of the averaged rms voltage decreases, and there is no change in the magnetizing field at peak.

Thus, MAE parameter changes can be understood on the basis of microstructure changes: the combined effects of cell texture and dislocations. However, further investigations are required to understand interactions between non-180° DWs and pinning sites in detail. Especially, DW observation is important and direct observation of interactions between DWs and pinning site is desirable.

5. Conclusion
This paper investigated the behaviours of MAE signals for low carbon steel with cold rolling related to their microstructure changes and the following results are clarified.

The rms voltage and the peak in averaged rms voltage reflect the number of pinning sites for non-180° domain wall motion. They rise sharply in an initial stage of cold rolling due to the increases in dislocation density. Then they decrease at higher reduction ratio since cell structures of dislocation may decrease the effective pinning sites. On the contrary, the magnetizing current at peak in the averaged rms voltage decreases monotonically due to the increase in dislocation with weaker interactions between pinning sites and DWs below 10 % reduction ratio. Since the development of cell structures of dislocation only decreases the number of pinning sites, the magnetizing current at peak is constant above 10 % reduction ratio.

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