AC MAGNETIC FIELD AMPLITUDE DEPENDENCE OF MAGNETOACOUSTIC EMISSION SPECTRA AND EFFECTS OF TEMPER EMBRITTLEMENT OF HY80 STEEL

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INTRODUCTION

Certain impurity species trapped in the grain boundaries of HY80 steel during the post-fabrication heat treatment are known to cause temper embrittlement [1]. On the other hand, the local residual stress fields due to lattice mismatch at grain boundaries are the main pinning sites causing irreversible magnetic domain wall motion that creates magnetoacoustic emission (MAE). The peak amplitude of MAE depends on two major factors; the waveform of applied AC magnetic field and the strength of the 90° domain wall-defect interaction which creates an effective potential barrier against the domain wall motion. As the degree of embrittlement increases, therefore, the peak amplitude of MAE burst should increase since the higher concentration of impurities enhances the 90° wall-defect interaction at the grain boundaries.

In our previous study, the MAE amplitude was seen to follow the above discussed effect only to a certain degree of embrittlement in HY80 steel samples [2,3]. Beyond this, it decreased and the relation between the MAE peak amplitude versus embrittlement is not a single-valued function. In addition, the MAE amplitude is dependent of the AC magnetic field strength which, in turn, depends on the actual geometry of a particular test arrangement. It is, therefore, necessary to devise an analysis method which does not rely on the MAE amplitude to determine the degree of embrittlement.

One noticeable feature in the spectral characteristics observed in the HY80 steel samples with a considerable degree of embrittlement is the asymmetry in the MAE burst [3]. It was believed that such an asymmetry may be a parameter useful in determining the degree of temper embrittlement but its origin has been unclear. The asymmetry in the MAE burst also appears in HY80 samples under uniaxial compressive stress when an AC magnetic field is applied parallel to the stress axis [4]. Hence it is necessary to perform a systematic investigation to clarify the effects of embrittlement and uniaxial compression on the shape of the MAE...
burst. A lack of AC magnetic field strength has been assumed to be the probable cause of the asymmetry in both cases [3,4]. In the present study the experiments were, therefore, repeated by using a power supply/amplifier with a considerably higher capacity over the one that was used in the past.

EXPERIMENTS

The six HY80 steel samples used in the previous study were re-examined in this study [1]. The experimental setup was also identical except the power supply/amplifier which has been upgraded as explained in the companion paper submitted in this conference [5]. Throughout the present experiments, the AC magnetic field frequency was kept at .7 Hz. The amplitude of the AC magnetic field was controlled by varying that of sinewave input to the power supply/amplifier from .5 V to 10 V in an interval of .5 V. The details of the samples and the setup can be found elsewhere [1].

RESULTS AND DISCUSSION

Fig. 1 and Fig. 2 show the results obtained with a sample which was unembrittled and the one which was embrittled by heat treatment for an hour, respectively, at 1.5 V sinewave amplitude input to the power supply/amplifier. Each spectrum contains an MAE burst with a two-peak structure. This is because, at this level of applied AC magnetic field, 90° domain walls move slowly over the major potential barriers that they encounter just before and after the coercive field point. Fig. 3 shows the results of the unembrittled sample at the maximum output of the power supply/amplifier. In contrast to that shown in Fig. 3, the results of the same measurement with the one hour-heat treated sample, shown in Fig. 4, apparently lacks a clear two-peak structure in the burst. This directly indicates a slower 90° domain wall motion in the grains of an unembrittled sample than that in the embrittled sample. Since the impurity concentration inside grains is higher in the unembrittled sample, 90° domain wall motion should be slower between the two major potential barriers. This is why the two-peak structure shown in Fig. 3 is more pronounced than that in Fig. 4. Hence the results of these four figures are consistent with the basic embrittlement-causing mechanism.

Fig. 5 shows the results obtained with a sample heat treated for 5 hours, at 6.5 V sinewave input to the power supply/amplifier. A very brief and sharp sub-peak can be seen in leading edge of the burst shown in Fig. 5. The presence of this short leading sub-burst will be discussed later. Fig. 6 shows the results obtained with the same sample at the maximum output of the power supply/amplifier. Some characteristics of the spectrum in Fig. 6, in comparison with that in Fig. 5, are the compression of MAE burst in time scale, the overall MAE peak amplitude that remained almost the same, and the removal of two-peak structure. A single MAE burst is produced by sweeping through a half cycle of hysteresis loop, i.e., from $H_{\text{max}}$ to $-H_{\text{max}}$. The MAE generation occurs due to domain wall motion rather than domain rotation. The compression of the MAE burst in time by an increase in the AC field amplitude clearly indicates the inclusion of domain rotation process in the hysteresis loop. The fact that the MAE amplitude remained almost the same despite the increase in the AC field amplitude indicates that the rate of 90° domain wall movement leveled off already under the condition of Fig. 5. Based on the above two facts, it is clear that the amplitude of AC applied magnetic field is sufficient.
Fig. 1. The results obtained with an unembrittled HY80 sample at 1.5 V sinewave input to the power supply/amplifier.

Fig. 2. The results obtained with the sample heat treated for 1 hour at 1.5 V sinewave input.

Fig. 3. The results of the unembrittled sample at 10 V sinewave input to the power supply/amplifier.

Fig. 4. The results of the sample heat treated for 1 hour at 10 V sinewave input.
Fig. 5. The results of the sample heat treated for 5 hours at 6.5 V sinewave input.

Fig. 6. The results of the sample heat treated for 5 hours at 10 V sinewave input.

Fig. 7 to Fig. 9 show the results obtained with the sample heat treated for 24 hours at 3.5, 7 and 10 V of the input sinewave amplitude. The results of Fig. 7 show an apparent tendency of asymmetric double-peak structure in the MAE burst as the sample becomes more embrittled. With an increase in the AC applied field amplitude, these two sub-peaks tend to collapse into a single asymmetric burst, as seen in Fig. 8. With the maximum output of the power supply/amplifier, the MAE burst is seen to slightly regain the symmetry as shown in Fig. 9.

Fig. 7. The results of the sample heat treated for 24 hour at 3.5 V sinewave input.
Fig. 8. The results of the sample heat treated for 24 hours at 7 V
sinewave input.

Fig. 9. The results of the sample heat treated for 24 hours at 10 V
sinewave input.

Fig. 10 shows the results obtained with the sample heat treated for
50 hours at 3.5 V sinewave amplitude. Compared with the results of Fig. 
7, it is clear that the smaller leading sub-burst tends to vanish as the 
sample becomes more embrittled. Such an asymmetry persistently appeared
until the input sinewave amplitude was increased up to 8 V, as shown in
Fig. 11 and, beyond this, the MAE burst is seen to be almost symmetric.
Fig. 12 and Fig. 13 show the results obtained at 9.5 and 10 input
sinewave amplitude, respectively. During the sweep over the hysteresis
loop, domain walls annihilated and recreate, and the state of 90° domain
walls is subject to a statistical fluctuation. The difference in pattern
of MAE burst shown in these two figures was probably caused by this
fluctuation. Nevertheless, it is apparent that the MAE burst in highly
embrittled HYSO steel samples is asymmetric in a certain range of applied
AC field amplitude. Beyond this region, the symmetry in the MAE burst
tends to appear as the applied AC field amplitude increases. Almost the
same AC field amplitude dependence of MAE pattern was observed in the
sample which was heat treated for 100 hours.

THE ORIGIN OF MAE ASYMMETRY DUE TO EMBRITTLEMENT

If the majority of 90° domain walls move back and forth between the
potential barriers at the grain boundaries, due to a lack of a sufficient
driving force, the uphill and downhill motions will cause different rates
of MAE generation. This has been assumed to be the main cause of the
 asymmetry in the MAE burst observed in the highly embrittled HYSO steel
samples [3]. It has been mentioned in the previous section that the
narrowing of the MAE burst width due to an increase in the AC magnetic
field amplitude is a direct evidence of pushing the hysteresis loop into
the region of domain rotation. At the same time, the overall MAE
amplitude was seen to level off at about 8 V of input sinewave amplitude. Based on these two facts, the AC applied field is considered sufficient to push 90° domain wall over the potential barriers in the highly embrittled HY80 sample. A lack of AC field strength thus cannot be regarded as the main cause of asymmetry any more.

Fig. 14 is a schematic illustration of the potential barriers with their peaks at the grain boundaries of an embrittled sample and the positions of 90° domain walls during the process between $|H_{\text{max}}|$ to $-|H_{\text{max}}|$. At the end of domain rotation the position of the 90° domain walls is at the location 1. As $B$, magnetic induction, approaches to $B_r$, the value at remanence, 90° domain walls execute uphill motion to location 2. During this process, an MAE sub-burst is created. After this, the applied field becomes negative and with a sufficient field strength the 90° domain walls jump over the barriers producing the second sub-burst. As the motion of 90° domain walls over the potential barriers (from location 2 to 3) produces the main MAE activity, the amplitude of second sub-burst should be always larger than that of first one. Depending on the rate of change in the applied magnetic field, the two peak-structure can collapse into an asymmetric single peak structure as discussed in the previous section. The asymmetry in the MAE burst thus generated due to embrittlement is always opposite to that due to uniaxial compression which creates a high amplitude in the leading edge of the burst [5]. The short leading sub-burst in Fig. 5 indicates that the 90° wall motion up to the remanence point and the subsequent motion over the potential barriers is rapid due to relatively low potential barrier compared to that of more embrittled samples.

Fig. 10. The results of the sample heat treated for 50 hours at 3.5 V sinewave input.

Fig. 11. The results of the sample heat treated for 50 hours at 8 V sinewave input.

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Fig. 12. The results of the sample heat treated for 50 hours at 9.5 V sinewave input.

Fig. 13. The results of the sample heat treated for 50 hours at 10 V sinewave input.

Fig. 14. A schematic illustration of the positions of 90° domain walls during a sweep in a half cycle of a hysteresis loop, i.e., between $|H_{\text{max}}|$ to $-|H_{\text{max}}|$.

SUMMARY

This paper presents the experimental results of AC applied magnetic field amplitude dependence of MAE spectra and the effect of temper embrittlement in HY80 steel. With an evidence that the intensity of applied AC magnetic field is sufficient to move the majority of 90° domain walls over the potential barriers at the grain boundaries, the previous assumption on the asymmetry had to be modified. Considering the dynamics of 90° domain walls of two different regions, before and after remanence, it was possible to explain the important characteristics of the asymmetry in the MAE burst caused by temper embrittlement.
REFERENCES


