APPLICATION OF MAGNETOACOUSTIC EMISSION TECHNIQUE TO TEMPER EMBRITTLEMENT CHARACTERIZATION OF HY-80 STEEL

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INTRODUCTION

Our previous work has shown that magnetoacoustic emission (MAE) is mainly contributed by the motion of 90° domain walls which lags behind that of 180° domain walls in phase [1]. The amplitude of MAE burst is always higher in the embrittled samples than in unembrittled one for a sufficient level of internal magnetic field. It has been also shown that for a small internal magnetic field, the MAE activity is higher in an unembrittled sample than is in embrittled ones. This is a direct evidence of the effect of potential barriers at the grain boundaries that determine the amplitude of the MAE burst under given conditions [2]. The pulse height analysis of the MAE spectral pattern has been included in our more recent work [3]. The results have shown that the Gaussian- like distribution broadens upon the decrease in impact strength of HY-80 steel samples due to embrittlement up to a certain level.

Such a trend, however, reverses as the samples become highly embrittled by heat treating for periods longer than 10 hours. It was assumed that, as the overall barrier height increases, some of the 90° domain walls fail to cross over the grain boundaries for a given level of internal magnetic field, and result in narrow distributions. In an effort to verify the above assumption, improvements were made in the magnetizing unit. To obtain information useful to explain the peculiarity observed in the highly embrittled HY-80 samples, it is necessary to gain a deeper insight of the MAE phenemena. For this purpose the effects of AC magnetic field frequency and shape have been included in the present study. In addition, the effect of uniaxial stress was studied and the results are presented in a companion paper submitted to this conference [4].

EXPERIMENTAL

The measurements have been repeated for the six HY-80 steel samples used in the previous work [1]. This set of samples consists of one without heat treatment and five samples with different hours of heat

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treatment at 538^{o}C after normal procedures of quenching and tempering. Details of the sample characteristics and heat treatment can be found elsewhere [5].

For the present study a pair of laminated core pieces were used while the overall geometry was kept the same as for the solid cores which were used in the previous work. Two waveforms of power supply/amplifier output, sine and square waves, were applied to activate a pair of eletromagnets surrounding the laminated steel cores. The AC magnetic field frequencies used for the main results of the present study were .7 Hz and 20 Hz. A digital storage scope was used to record the MAE spectra and a multichannel analyzer was used for the direct construction of histograms by collecting ten million MAE events for each. For the construction of histograms in the present experiment, the low level discriminator of the maultichannel analyzer was adjusted to exclude the system backgorund noise. The details of the experimental procedure can be found in the references cited above.

RESULTS AND DISCUSSION

Effects of Rate of Flux Change on MAE Pattern

Fig. 1 shows the MAE spectrum and pickup coil output obtained with the unembrittled HY-80 steel sample by applying 20 Hz sine wave output from the power supply/amplifier. The impact strength of this sample is about 127 ft-Lbs. The MAE spectrum in this figure shows a clear separation between bursts. Each MAE burst was produced by sweeping the magnetic field over one half cycle of the hysteresis loop. The narrow band that appears between two bursts is due to the background noise in the detection system. Fig. 2 shows the results obtained by applying 20 Hz square wave output from the power supply/amplifier to the same sample.

Comparing the results of these two figures, it is clear that the square wave-like form of pickup coil output results in a higher peak amplitude of the MAE burst. For the purpose of analysis in terms of B-H curve, we suppose $B=-B_{max}$ at (a) in Fig. 2. Moving along the portion of B-H curve between $-B_{max}$ and $-B_r$, where B_r is the remanence, the rate of flux change increases slightly but the MAE activity in this process should be very low. Beyond $-B_r$, the major domain wall motion occurs right before and after B=0, or $H=-H_c$ where H_c is the coerceive field, causing a sudden increase in B which is followed by the most pronounced MAE activity. The slope of B-H curve is steepest at B=0, in general, which corresponds to the point (b) in the figure. The time span between $B=-B_{max}$ and B=0 in Fig. 2 is somewhat shorter than that in Fig. 1 due to a faster movements of 90^{o} domain walls over the major pinning sites causing a higher peak amplitude of MAE burst. Past the major irreversible domain wall motion region right after (b), induction B keeps increasing until it reaches (c). The sub-burst structure before (c) is assumed to be due to unpinning of the 90^{o} domain walls that encounter those grain boundaries with somewhat severe lattice mismatch.

Fig. 3 shows the results obtained with the same sample by applying .7 Hz square wave output from the power supply/amplifier. The shape of the pickup coil output of this figure shows very rapid transition between the various positions in the B-H curve, but the peak MAE amplitude in this case is not any larger than that seen in Fig. 3 (Notice the change in the vertical scale of the upper trace). This is due to an extremely shallow penetration depth and possibly a lack of time that the majority of 90^{o} domain walls need to respond the rapidly changing flux. The optimization of waveform of the applied magnetic field, therefore, should include such considerations.

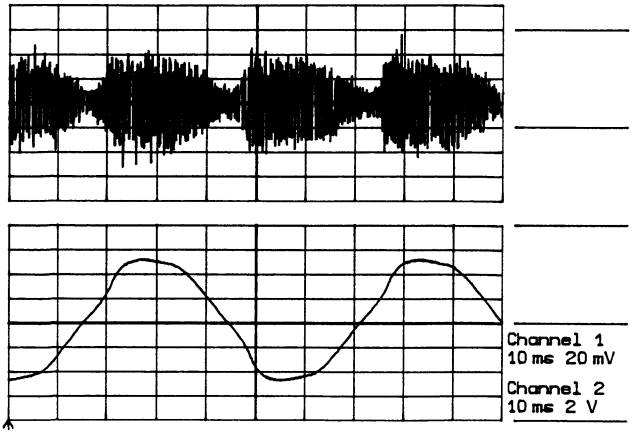

Fig. 1. The MAE sprectrum and pickup coil output obtained with an unembrittled HY-80 steel sample by applying 20 Hz sine wave output from the power supply/amplifer.

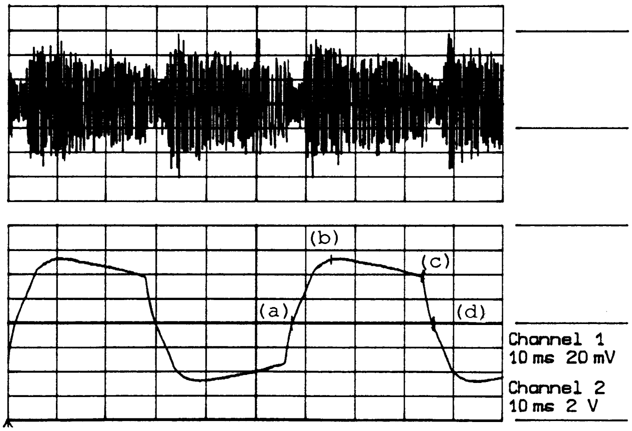

Fig. 2. The results of the repeated measurements of Fig. 1 by applying square wave output from the power supply/amplifer.

Fig. 3. The results obtained for the unembrittled sample by applying .7 Hz square wave output from the power supply/amplifier.

MAE Waveform vs. Histogram

Fig. 4 show the results of the repeated measurement of Fig. 3 with a HY-80 steel sample which was embrittled by heat treating at 538° C for 5 hours and its impact strength is about 15 ft-Lbs. Except the overall MAE peak amplitude, the MAE waveform in Fig. 4 does not show any other difference in spectral characteristics from that shown in Fig. 3.

Fig. 5 shows the results of pulse height analysis of the MAE spectra obtained under the experimental conditions of Fig. 3 and Fig. 4. The histograms were constructed from the MAE spectra of the unembrittled, and two embrittled samples which were heat treated for 1 and 5 hours. The impact strength of the sample with 1 hour heat treatment is about 55 ft-Lbs. The curve obtained for the unembritteld sample shows a distribution which can be fitted to a single Gaussian function. The curves representing the results obtained for the samples with 1 hour and 5 hour heat treatments, on the other hand, show some noticeable differences. At the begining, these curves decrease rapidly and at about channel 300 their curvature changes in a way that the count rate after this channel appears to be enhanced for a range that extends roughly to channel 500. Such an effect is found to be unique for the pickup coil output shown in Fig. 3 and Fig. 4.

In an attempt to understand the origin of the above effects, it is necessary to consider the locality of the 90° domain wall-defect interaction. The 90° domain walls encounter, during their motion, individual grain boundaries with different geometry and concentration of certain impurities. A varying degree of strength exists in the interaction, as a function of position and time. It is then assumed that the interaction of a certain range of strength is more sensitive to a particular form of applied magnetic field. Apparently, such a detailed information on the 90° domain wall-defect interaction is not available directly from the MAE spectra.

Effects of Embrittlement

These curves in Fig. 5 show that the effect of embrittlement is to broaden the distribution due to the increased count rate in higher amplitude MAE signals. This is due to the fact that grain boundaries become more rigid obstacles for 90° domain wall motion. Unpinning of 90° domain walls in more embrittled samples cause more abrupt motion of these walls resulting in higher amplitude MAE pulses. If this assumption is correct, a further broadening of the distribution should be obseverd in more embrittled samples.

Fig. 6 shows the histograms obtained for the further embrittled samples. These samples have been heat treated for 24, 50 and 100 hours and the corresponding impact strengths were 9.5, 6.5 and 5.0 ft-Lbs. The results in this figure show a trend that is reversed from that seen in Fig. 5. All the sets of histograms obtained at any other experimental conditions show the similar effects of embrittlement seen in these two figures. There are two reasons being speculated for the cause of such a reversed trend.

A lack of sufficient magnetic field intensity is currently considered as the prime reason. If the applied magnetic field is not capable of providing a sufficient driving force for the unpinning of the major 90° domain walls, fewer high aplitude MAE pulses are created. The next factor to be considered is the changes in impurity constituents in the grain boundaries due to the heat treatment in longer periods. This is because the impurity atoms are constantly trapped and detrapped at the grain boundaries while they were undergoing the thermally activated

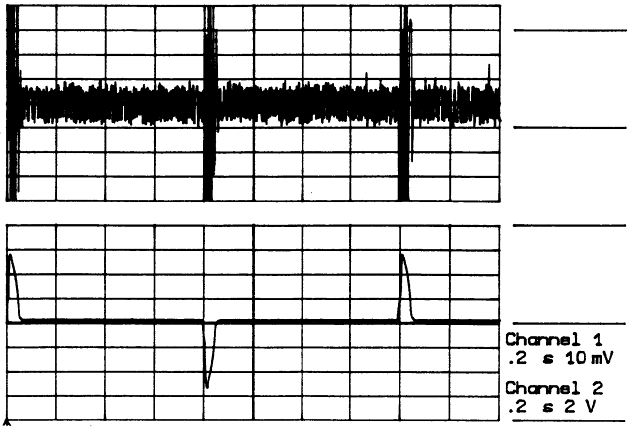

Fig. 4. The results obtained for the sample heat treated for 5 hours under the same experimental conditions of Fig. 3.

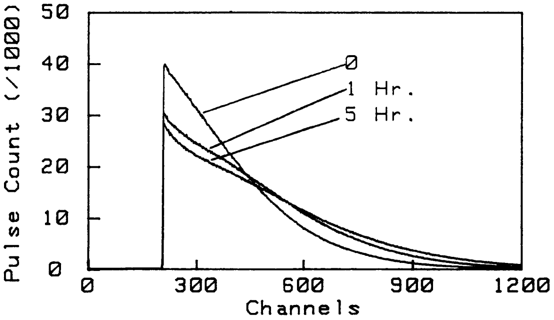

Fig. 5. The results of pulse height analysis for three samples: unembrittled, and embrittled by 1 hour and 5 hours of heat treatments.

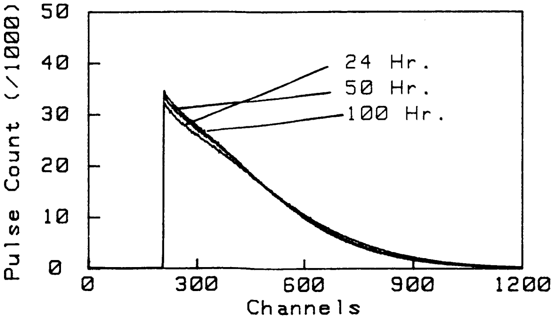

Fig. 6. The results of pulse height analysis for the samples heat treated for 24, 50 and 100 hours.

diffusional motion during the heat treatment. It is well known that only certain types of impurities trapped in the grain boundaries cause embrittlement. The rates of thermally-activated diffusional motion and trapping at the grain boundaries are different for different types of impurity atoms.

The height of potential barriers at the grain boundaries is mainly affected to the total concentration of impurity atoms, while the impact strength of the material is directly related to the concentration of embrittlement-causing atomic species. It can be then assumed to be: First, the total concentration of impurities at the grain boundaries is highest in the sample which has been heat treated for 5 hours. Second, the heat treatments over longer periods result in a decrease in the total concentration but an increase in that of the embrittlement-causing impurity atoms at the grain boundaries.

The experimental base of the assumption, a lack of driving force on the 90° domain walls that causes the asymmetry in the MAE burst of highly embrittled samples, has been reported partially in the previous study [1]. Using a different form of applied AC magnetic field, more dramatic results were obtained in the present study. Some of these new results obtained by applying .7 Hz sine wave output from the power supply/ amplifier are presented in the next figures.

Fig. 7 shows the results obtained for the unembrittled sample. The MAE burst in the figure is seen to be symmetric, as expected. In this figure, the MAE activity is almost independent of the rate of flux change. Fig. 8 shows the results obtained with the sample heat treated for 5 hours. For the measurements of Fig. 8, asymmetric bursts occasionally appear in the spectrum. This is because the 90° domain walls undergo many cycles of annhilation and recreation, which involve certain degree of irreversibility, and each cycle is subjected to a statistical fluctuation. The asymmetric burst also shows a clearer double-peak structure which indicates a slower 90° domain wall motion between the major barrier peaks. Although more detailed analysis has yet to be made, the 90° domain wall motion is seen to be very active in this figure. Fig. 9 show the results obtained with the sample heat treated for 50 hours and the asymmetry in the MAE burst is clearly seen in this figure. Such an asymmetry pattern appears in the results obtained for the samples heat treated for 24 and 100 hours.

The results presented in these three figure strongly supports the above assumption of a lack of driving force in the highly embrittled samples. At the same time, our previous study showed a slight drop in remanence for the sample heat treated for 100 hours compared to that of the samples heat treated for 24 and 50 hours [5]. This indicates that the other assumption, variation in the impurity constituent at the grain boundaries as a function of heat treament time, may also be valid to a certain extent.

Based on the experimental evidences obtained so far, the increase in the AC magnetic field intensity should enhance the MAE activity in the highly embrittled samples and clarify the validity of the above assumptions. On the other hand, there is a possibility that the strong resistance against the 90° domain wall motion towards the top of the barrier peaks in these samples may persistently repeat the present trend regardless of the AC field intensity. Nevertheless, a strong correlation between the asymmetry in the MAE burst and the degreee of embrttilement has been confirmed. A separate study on the other asymmetry-causing factors has been also performed. The experimental results of the companion paper presented in this conference show that the presence of uniaxial compressive stress in the material causes such an asymmetry [4].

Fig. 7. The results obtained with the unembrittled sample by applying .7 Hz sine wave output of power supply/amplifier.

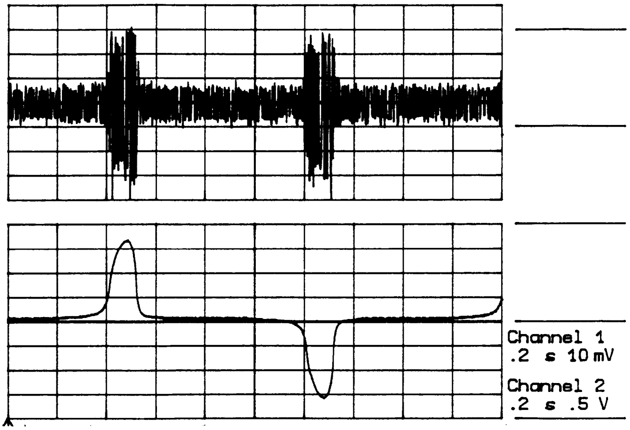

Fig. 8. The results obtained with the sample heat treated for 5 hours under the same experimental conditions of Fig. 7.

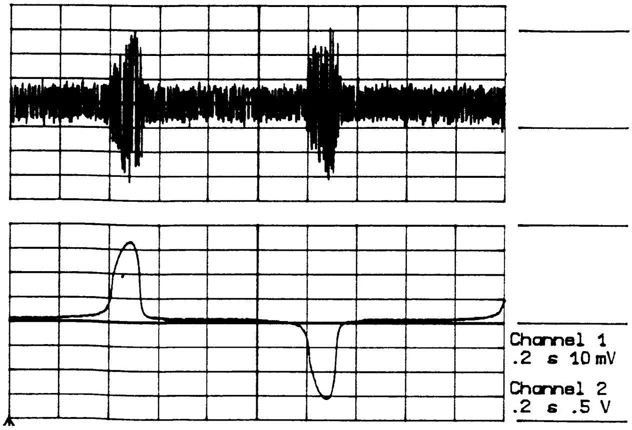

Fig. 9. The results obtained with the sample heat treated for 50 hours.

SUMMARY

The peak amplitude of MAE burst, which is directly related to the width of the pulse height distribution, has shown to be a critcal parameter in the determination of the degree of temper embrittlement in HY-80 steel. Our previous results showed, however, that the expected effect of temper embrittlement was consistent only up to a certain degree and it reversed slightly in the samples with higher degrees of embrittlment. The present study was performed to clarify such a reversal by performing measurements under various experimental conditions and with an improved magnet core design. The results still show such a reversal and it bacame more evident that a further improvement is needed in producing a higher intensity of the AC magnetic field. The present study, however, revealed more interesting information on the MAE spectral characteristics related to the waveform of applied AC magnetic field, and the uniqueness of information obtained directly from the MAE pattern and the pulse height distributions. Added is a detailed dicussion on the two possible factors causing the reversal. The asymmetry in the MAE burst of the highly embrittled samples presented in this paper is seen to be much clearer than that observed in the past.

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