EFFECTS OF UNIAXIAL STRESS ON MAGNETOACOUSTIC EMISSION AND
MAGNETOACOUSTIC RESPONSES IN STEEL


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INTRODUCTION

Among the several unique phenomena observed during the irreversible domain wall motion in a ferromagnet, the Barkhausen and AE-type effects have been extensively studied due to their sensitivity to the material properties and residual stress state [1,2]. Between these two effects, the former is based on the abrupt motion of domain walls over pinning sites and the latter is based on the progressive rearrangement of domain structure following the magnetization process. A series of acoustic noise events, which occurs almost simultaneously with the magnetic Barkhausen noise, provides a separate methodology with unique capabilities and is the base of the magnetoacoustic emission (MAE) technique. The practical application of the AE-type effect to NDE residual stress measurement involves measuring \( \Delta F(B)/F \), fractional changes in frequency of phase-locked acoustic waves as a function of net magnetic induction, and the method has been called the low-field magnetoacoustic (MAC) technique by some of us [3].

The uniqueness of the MAC technique is the presence of the negative initial slope of \( \Delta F(B)/F \) curves when net magnetization is induced parallel to the uniaxial compressive stress axis. The detection of uniaxial compressive residual stress is, therefore, possible without requiring a calibration standard. The detection of uniaxial tensile residual stress, however, is not possible due to the fact that \( \Delta F(B)/F \) curves obtained under tension lie under that of the unstressed state with some exceptions for certain types of steel [4].

In the present study, the uniaxial stress dependence of the MAE phenomena has been investigated and compared with the MAC measurements performed with the same sample. The results show that the MAE technique is capable of detecting the presence of uniaxial residual tensile stress. This, however, is true only if one can be sure of the
existence of sufficient magnetic field intensity and, at the same time, the absence of compressive residual stress in the object. The combination of the MAE and MAC techniques, therefore, is necessary for reliable characterization of the residual stress state in a ferromagnet since the two techniques complement each other.

UNIAXIAL STRESS EFFECTS ON MAE RESPONSES

The lattice and ferromagnetic systems interact with each other through the magnetoelastic interaction. The minimization of this interaction energy causes an anisotropic deformation of lattice unit cells, called spontaneous magnetostriction [2,5]. An application of uniaxial stress adds an angular dependence, which involves the angle between the uniaxial stress axis and the magnetization vector of each domain, to the interaction. As a result, the ferromagnetic state readjusts first by moving the domain walls. The rotation of domain magnetization due to uniaxial stress is possible but is negligible in iron and most of iron base alloys. For ferromagnets with positive spontaneous magnetostriction coefficients, the domains align parallel to the tensile stress axis, and they align perpendicular to the compressive stress axis [2,5].

Two types of domain walls exist in these ferromagnets: $90^\circ$ and $180^\circ$ walls. Under uniaxial tension, the area of $90^\circ$ domain walls gradually decrease upon the increase in stress amplitude and the domain structure becomes uniaxial. Under uniaxial compression, however, the domain structure is multiaxial and the area of $90^\circ$ domain walls directly affected by the magnetic field applied parallel the stress axis, begins to increase slightly. After reaching its maximum, the area of these $90^\circ$ domain walls begins to decrease as the magnitude of compressive stress increases.

The main factors that determine the spectral characteristics of MAE patterns are the area of $90^\circ$ domain walls and the rate of their movements, and the state of lattice defects. Since the application of uniaxial stress affects the area of $90^\circ$ domain walls, the uniaxial stress dependence of MAE generation is expected to follow that of $90^\circ$ domain wall area.

The axial symmetry of domain structure about the uniaxial stress axis is preserved with an external field applied parallel to the same axis, while it is not when the field is applied in any other direction. Our previous work on the MAC measurements showed that the interpretation is more difficult for the results obtained by applying the magnetic field perpendicular to the uniaxial stress axis [7]. Since this must be true also for the MAE measurements, the main experimental results and the follow-on discussions in this paper concern primarily to the case of field application parallel to the stress axis.

EXPERIMENTAL

The sample used in this experiment was obtained from a HY-80 steel cast block which has not been subjected to any stress-relief heat treatment. The sample was originally machined to be a cylindrical bar, which was then machined to obtain a rectangular cross-section of $16 \, \text{mm} \times 14 \, \text{mm}$ for a gauge length of $105 \, \text{mm}$. Uniaxial stress was applied up to $\pm 200 \, \text{MPa}$ in intervals of $25 \, \text{MPa}$. For the MAE measurements, 20 Hz sine wave output from the power supply/amplifier was used to activate a pair of electromagnets and C-shaped cores. For the MAC measurements, 5 MHz compressional waves were propagated perpendicular to the uniaxial stress axis in the pulse-echo mode. The detailed experimental procedures of the both techniques can be found elsewhere [6,7].
RESULTS AND DISCUSSION

Fig. 1 shows the MAE spectrum and the corresponding pickup coil output of the sample in the unstressed state and an AC magnetic field applied parallel to the cylindrical axis. The distortion in the pickup coil output is due to the eddy current generated by opposing magnetic flux changes in the sample. The MAE activity is seen to be consistent with the shape of the pickup coil output, i.e., the MAE pulse amplitude is generally higher where the slope of pickup coil output is steeper.

The effect of applied tension is seen to decrease the MAE amplitude as expected. Fig. 2 shows the results obtained at 100 MPa which was applied parallel to the cylindrical axis. The pickup coil output in this figure is seen to be slightly more distorted compared to that shown in Fig. 1. This is because 180° domain walls begin to dominate the domain structure under tension and the rate of the domain wall motion-induced flux change becomes higher.

![Fig. 1. The MAE spectrum obtained for the unstressed state by applying an AC magnetic field parallel to the cylindrical axis.](image1)

![Fig. 2. The MAE spectrum obtained by applying the AC field parallel to the uniaxial tensile stress axis of 100 MPa.](image2)
The effect of small amplitude uniaxial compression is seen to increase the MAE activity. Fig. 3 shows the results obtained at -50 MPa where the amplitude of MAE burst is seen to be enhanced and the pickup coil output is less distorted compared to that shown in Fig. 1. The results in this figure undoubtedly indicate the enhanced activity of $90^\circ$ domain walls which was expected by the uniaxial stress-induced domain alignment. The more important facts in these results, however, are the asymmetry and the appearance of double peak structure of the MAE burst. These are due to the motion of $90^\circ$ domain walls that is significantly slowed down, as reported in our previous work which used the AC magnetic field frequency of .7 Hz, whereas the present study used 20 Hz.

Fig. 4 shows the histograms representing the pulse height distributions of the MAE spectra obtained at the unstressed state and at selected levels of uniaxial stress with the AC field applied parallel to the stress axis. The results clearly indicate that the effect of tension is to monotonically decrease the width of the distribution. The effect of uniaxial compression is seen to increase the width of distribution at low stress levels, and begins to decrease it as the stress magnitude increases.

Fig. 3. The MAE spectrum obtained applying the AC field parallel to the uniaxial compressive stress axis of -50 MPa.

Fig. 4. The histograms for the MAE spectra obtained for the unstressed and under uniaxial stress by applying the AC field parallel to the stress axis.
Fig. 5 shows the results obtained at -50 MPa by applying the AC magnetic field perpendicular to the uniaxial stress axis. None of the results obtained with this magnetization scheme showed any particular form of MAE pattern under uniaxial stress. For a direct comparison, each histogram was fitted to the Gaussian distribution, \( N(x) = N_0 \exp(-\sigma^2 x^2) \), where the width of the distribution is directly influenced by the magnitude of \( \sigma \). The results are summarized in Fig. 6. As seen in this figure, the trend in the uniaxial stress effects on the MAE spectral characteristics is not particularly different for two different magnetization schemes. This means that the MAE technique alone cannot distinguish the presence of tensile residual stress from that of compressive stress.

The extremely low level of MAE activity under relatively high tensile stress seen in Fig. 4, however, can be a strong indication of the presence of residual tensile stress. Nevertheless, one has to make sure, in this case, that a sufficient AC magnetic field exists in the object and the presence of residual compressive stress can be completely excluded.

Fig. 5. The results obtained at -50 MPa by applying the AC field perpendicular to the stress axis.

Fig. 6. The magnitudes of \( \sigma \) as a result of a Gaussian fitting of the histograms obtained at different uniaxial stress levels and for two different directions of applied AC magnetic field.
Fig. 7. $\Delta F(B)/F$ curves obtained for unstressed state and under uniaxial stress by applying an external magnetic field parallel to the stress axis.

Fig. 8. $\Delta F(B)/F$ curves obtained for unstressed state and under uniaxial stress by applying an external magnetic field perpendicular to the stress axis.
The results of MAC measurements are shown in the next two figures. Fig. 7 shows the results obtained by incrementally applying DC magnetic field parallel to the uniaxial stress axis. As seen in this figure, there is almost no difference between the curves obtained in the unstressed state and under 200 MPa. All the other tension curves are positioned between these two curves. The curves under compression, however, show a good separation between the stress levels. Fig. 8 shows the results obtained by applying the external field perpendicular to the uniaxial stress axis. The curves in this figure show similar effects of uniaxial stress seen in Fig. 7. The steep negative slope under uniaxial compression shown in Fig. 8 actually has never been observed in other types of steel samples with such a magnetization scheme. Nevertheless, the results in both Fig. 7 and Fig. 8 reaffirm that the MAC technique is capable of detecting the presence of residual compressive stress.

FURTHER DISCUSSION ON THE MAE CHARACTERISTICS

With the application of AC magnetic field parallel to the stress axis, the peak amplitude of MAE burst increased under -50 MPa, as shown in Fig. 3. Similar results were obtained at -75 MPa. Beyond this, the amplitude of MAE burst begins to decrease as the magnitude of compressive stress increased. This is consistent with the well-known uniaxial stress-induced domain alignment in this type of ferromagnet. The double-peak pattern and asymmetry in the MAE burst appeared in the range between approximately -50 MPa and -75 MPa. As the magnitude of compressive stress increases, the asymmetry disappeared but the double-peak pattern sustained. The details of the compressive stress dependence of these two characteristics are discussed in the following.

The double-peak pattern has been regarded as a characteristic of an MAE spectrum obtained with an AC magnetic field frequency much lower than 20 Hz which was used in the present study. The appearance of this pattern in the MAE burst at .7 Hz was reported in our previous work [7]. Such appearance was attributed to the slow rate of flux changes that allows the 90° domain walls to spend sufficient time between two major potential barriers that these walls encounter just before and after ±Hc, where Hc is the coercive field. If the rate of 90° domain wall movement is lowered independently, the double-peak pattern in the MAE burst should appear almost regardless of the AC field frequency.

The asymmetry in the MAE burst has been observed previously only in the highly embrittled, residual stress-free, HY-80 steel samples [7]. The effect of embrittlement in this ferromagnet is to increase the height of the effective potential barriers, resisting the 90° domain wall motion, at the grain boundaries. Each 90° domain wall moves along a different path during the field-induced domain wall motion process. Some of these domain walls encounter stronger barriers and fail to execute their complete motion. The rate of 90° domain movements under this condition should be different for the motion towards the top of the barrier and that in the opposite direction. Since the MAE activity is a function of the rate of 90° domain wall movement, an asymmetry appears as the potential barriers are enhanced. If the external magnetic field-induced driving force is such that some 90° domain walls fail to complete their motion, the asymmetry in the MAE burst also appears.

According to the above discussions, the presence of uniaxial compression must be to slow down the 90° domain wall motion that is
induced by an AC magnetic field applied parallel to the stress axis. This is exactly consistent with what can be expected from the various interactions. Upon the application of uniaxial compression, the domains tend to align perpendicular to the stress axis. Under this condition, any 90° domain wall motion, due to applied magnetic field, that increases the total magnetoelastic energy of the system will face a resistance. The presence of uniaxial compression, hence, tends to slow down the 90° domain wall motion. For the range of -50 MPa and -75 MPa, the combined effects of compressive stress-induced resistance of 90° domain wall motion and the momentary increase in the area of these walls seem to be the main cause of the spectral characteristics described above. With the magnitude of compressive stress beyond this range, less 90° domain walls are available and their motion becomes even slower to produce smaller peak amplitude of MAE burst. At the same time, the symmetry in the spectrum is restored.

SUMMARY

This paper presents the results of the MAE and MAC measurements performed with an unembrittled HY-80 steel specimen. The main results of the MAE measurements were obtained by applying an AC magnetic field of 20 Hz parallel to the uniaxial stress axis. The effects of tensile stress were found to monotonically decrease the peak amplitude of MAE burst, and is consistent with the predicted trend based on the tensile stress-induced domain alignment. The effects of compressive stress were found to increase the peak amplitude of MAE burst initially and to eventually decrease as the magnitude of compressive stress increased. Such effects of uniaxial compression are also consistent with the predicted trend. The asymmetry of the MAE burst observed in the range of -50 MPa to -75 MPa and the restoration of symmetry under higher levels of compressive stress were explained based on the lower rate of 90° domain wall movements under these conditions.

It was shown that the MAE technique is probably not capable of detecting independently the presence of uniaxial tensile stress. It seems, however, possible if the absence of compressive residual stress and the existence of a sufficient magnetic field intensity in the object can be verified separately. The results of the MAC measurements, of course, reaffirmed that the detection of residual compressive stress can be accomplished without requiring a calibration standard.

REFERENCES


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