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ACOUSTIC RESPONSE OF DYNAMIC PIEZOMAGNETIC BEHAVIOR

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ABSTRACT

The coupling between the self-generated magnetic and acoustic behavior of magnetostrictive materials under load is explored. Results from fatigue loading of magnetostrictive ferromagnetic materials suggests that the acoustic response is sensitive to internal stress rates. Acoustic wave propagation can travel in the material with less damping than the magnetic behavior that created it. This suggests an ability to measure this behavior remotely. The hypothesis is that this noise is related to piezomagnetic behavior and the discontinuous nature of local changes in magnetic permeability. Various materials were tested in compression and tension. Non-magnetostrictive specimens do not exhibit this behavior. Specimens with smaller magnetostriction exhibit the behavior with less intensity. A reduction of this behavior does occur as the loading frequency is increased. Understanding the sources of this noise could yield a unique method for characterizing the early damage state of ferromagnetic materials and become the basis for smart sensor materials for characterizing structures.

Keywords: magneto-elastic noise

1. INTRODUCTION

Acoustic emission (AE) measurements in ferromagnetic materials have been plagued by noises that do not appear in AE measurements made in other metals. This effect can make the detection of specific crack growth problematic. These noise sources have been attributed to magnetic strain effects [1] but have been generally ignored or suppressed as they interfere with the main focus of the AE testing (crack growth). As materials, designs, and manufacturing methods have progressed, the aerospace field has been actively working to reduce mass while increasing strength and durability. This is driving the size of a "critical flaw" closer and closer to the scale of the microstructure. Detecting smaller defects is a challenge for existing testing modalities and is driving development of more capable techniques.

PMAE (Piezomagnetic Acoustic Effect) refers to acoustic noise generated in magnetostrictive materials when elastically strained. We think this noise arises from internal magnetic domains interacting with the microstructure of the material. It is suggested that any plasticity or changes in the microstructure that presage plasticity should change the noise.

The basis of this concept derives from two coexisting processes that exist in magnetostrictive materials along with the hypothesis that the effect of these processes combined will generate ultrasonic noise. The first process is piezomagnetism, also known as the Villari Effect [2] (inverse magnetostriction), whereby the application of stress affects magnetic permeability. It is a usually considered a bulk effect but it does arise from changes in the microstructure being stressed. The second effect is that the magnetic permeability change occurs locally in a discontinuous manner due to magnetic domain wall movement being pinned and unpinned at microstructural features. This latter effect is the well-known cause of Barkhausen Noise [3]. This electrical noise has a lattice vibration corollary that manifests itself as acoustic noise called, Magnetic Acoustic Emission (MAE) [4-8]. Applications of both effects has historically required the application of large external magnetic fields.

This paper expands an investigation [9] of this self-generated ultrasonic noise in magnetostrictive materials, which could lead to interesting measurement processes. It may be possible to treat magneto-elastic materials as a viable smart material system that can characterize dynamic behavior as well as identify early failure onset.

2. MATERIALS AND METHODS

The results presented in this abstract are from Terfenol-D, an iron alloy material that was chosen for its large magnetostrictive behavior. This material is very brittle, so the loading was restricted to compression fatigue in the elastic regime. Precautions were taken to eliminate interference from external piezomagnetic acoustic emissions from test equipment, by using rubber isolation, fused quartz platens, and inches of distance from the nearest ferromagnetic material. Because of these precautions, displacement/strain gauges were not used for these tests, so the data is presented as a function of applied stress. The frequency of the fatigue loading was 1 Hz. The minimum

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applied compression stress was about 0.5 ksi. The maximum compression was kept constant for sets of tens of cycles, but varied between sets from 1 ksi to 10 ksi, in steps of 1 ksi. This was well below the material's reported compressive strength (45 ksi-125 ksi). However, during testing, there were still occasional large amplitude signals with the characteristics of traditional AE crack-like signals that indicated irreversible damage as the sample was fatigued. These types of AE signals were filtered out during data reduction. Changing the maximum compression created maximum stress rates that varied from about 4 ksi/sec to 32 ksi/sec.

Resonant high sensitivity AE sensors and an AE data acquisition system were used to do waveform capture of the acoustic noise. However, unlike traditional AE, the system was triggered at a steady rate of 40 times per second, regardless of the signal amplitude. Capture duration was 102.4 microseconds digitized at a sampling rate of 10 MHz. Each noise waveform (sensor voltage V vs. time t) was reduced to a single number by calculating the energy of the signal in a traditional manner as:

$$Signal\ Energy = \sum_{i=1}^{n} V_i^2 \, \Delta t \qquad (6)$$

3. RESULTS AND DISCUSSION

Figure 1 shows the output of one of the noted sets versus time. The solid black line is the load profile. This particular set has maximum load of 800 lbs. (8 ksi). Each red dot represents the signal energy calculated from one of the sequential noise waveform captures. There is some variation in the pattern, but the overall repetition illustrates that these microstructural noise processes are reversible.

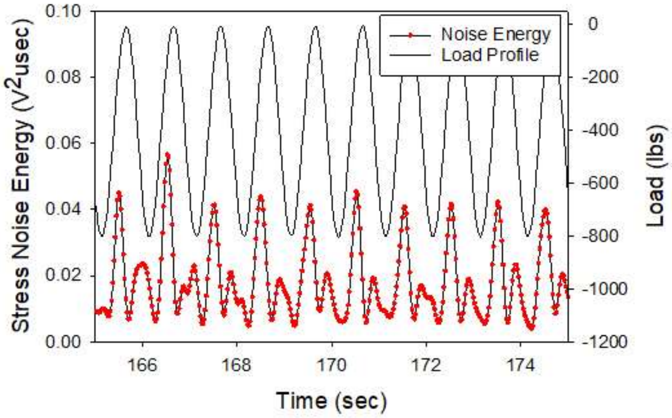

FIGURE 1: LOAD PROFILE AND STRESS NOISE FOR ONE SET OF 10 FATIGUE CYCLES

Figure 2 shows the repetition in Figure 1 reduced to an "average" cycle where each dot represents the average of the calculated signal energies from all the waveforms collected at the same phase points. Red error bars of one standard deviation show the similarity of the behavior from cycle to cycle. The signal energy falls to minimum values near both the minimum and maximum points in the load cycle, at 0.0 and 0.5 seconds, respectively. This illustrates that the response is not proportional to the loading and in fact oscillates with a predominate component at twice the load frequency. The local maximums of the signals align more with the points of highest rate of applied stress at 0.25 and 0.75 seconds. The fact that the signal minimums and maximums do not align exactly at the noted locations could be attributed to hysteresis of magnetic domain movement through material microstructure.

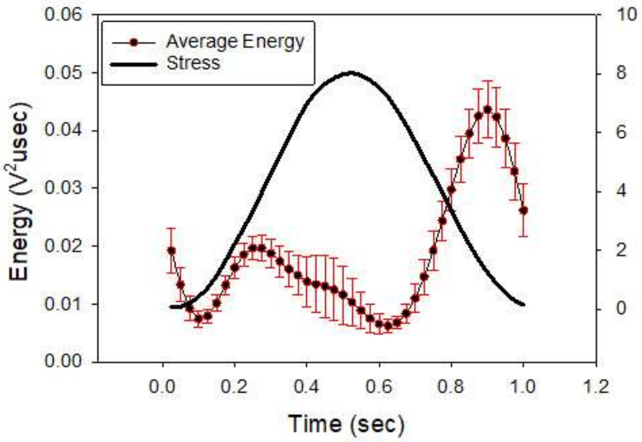

FIGURE 2: STRESS NOISE ENERGY

Figure 3 is a plot of the resultant maximum stress noise energy versus peak stress rate from a series of sets where the maximum applied stress varied from 1 to 10 ksi as noted before. Each data point is a statistic from each set of similar fatigue cycles. The error bars of one standard deviation illustrate the small variation in the peak over all the cycles in the set. As the stress rate increases, the signals show a relatively linearly increasing noise response.

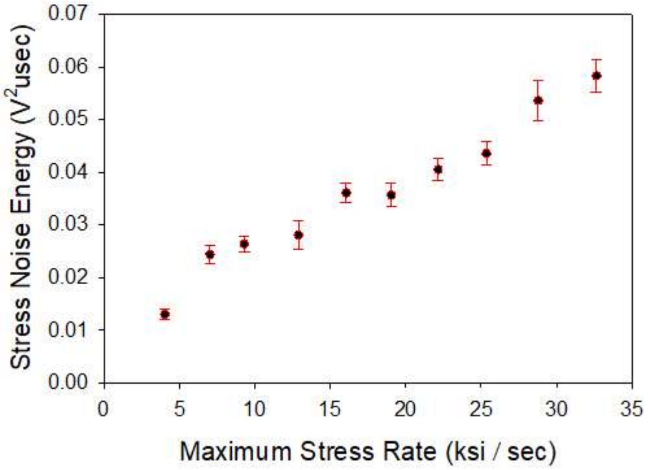

FIGURE 3: STRESS NOISE SIGNAL ENERGY OF TERFENOL-D IN COMPRESSION FATIGUE.

It is noted that in Figure 2 the greatest noise levels are evident during the off-loading half of the cycle as the stress is returning to zero. This suggests a large release of domain pinning during that part of the cycle. Results at smaller fatigue ranges, not shown here, have comparable values of the local maximum noise energies, and align in closer phase to the points of maximum stress rates. This could indicate less interaction with microstructure and that pinning energy distribution over strain, is not uniform.

Baseline tests with non-magnetostrictive samples of aluminum and copper, as expected, do not exhibit this behavior. Test on materials with smaller coefficients of magnetostriction exhibit this behavior, albeit with less intensity. Tests in tension were also performed on materials that exhibit good ductility. One of these, Galfenol, another large magnetostriction coefficient material, exhibits a reduction in this behavior as the loading frequency is increased.

4. CONCLUSION

Results from experimental fatigue loading of ferromagnetic materials suggest that tracking energy of the acoustic noise response in a stress regime below failure can be used to measure stress rates. It is shown that this acoustic response is due to the magnetostrictive properties of ferromagnetic materials and, as such, is available in other steel alloys. This acoustic response occurs without a large applied magnetic field suggesting that the same properties measured by other techniques that require applied magnetic fields, can be measured with less complex equipment. Deviations from expected behavior suggests that measurement of these deviations may be sensitive to changes that are precursors to damage and subsequent failure. These measurements can be made remotely because the acoustic signal can propagate away from the source with significantly less attenuation than the suggested magnetic behavior that created it.

Directly, this method will be able to provide a new method for monitoring a material's stress rate. This can be done whether the material is in plane stress or plane strain. Applications could include structures undergoing flutter or oscillations, vehicle crash performance, material yielding, and possibly impact/ballistic response, where high strain rate effects are of concern regarding the strength of these materials. It may be useful as a method of monitoring ductile material for tearing and failure precursors as those material events can involve rapidly changing local stress states. In appropriate applications, remote detection and location of high strain rate events that can predict pending damage in unexpected locations and at unexpected times should allow better structural management and safety. In general, the method could also have relevance to measuring dynamic stress concentration factors in ferrous materials. This method could be extended to non-magnetic materials, such as composites, by the embedding of the magneto-elastic materials. In fact, the method could be applied to the application of composite repair patches on aircraft where the certification of composite patches is problematic and incorporation of this concept might allow monitoring the integrity of the patch.

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