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16. Abstract

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Laboratory testing of steel specimens A588 and HPS70W with and without hydrogen charging were conducted. A588 was selected in part due to material availability and because its mechanical properties were reasonably close to under matched weld metals used with HPS70W. Acoustic emission (AE) monitoring was used as the means of detecting plastic zone formation, crack extension, and possible microcracking due hydrogen embrittlement. Although there is strong evidence to suggest that hydrogen-induced microcracking can occur in weld metal of bridge steels, including HPS70W, AE monitoring did not detect the formation of such damage in this study.

The following recommendations are offered:

1. If the costs associated with detecting and repairing delayed, or cold, cracking due to hydrogen embrittlement are considered too high despite infrequent occurrence, every precaution possible should be taken. This would include preheating the steel, either baking the consumables or using specially packaged consumables, and post heating to drive off excess hydrogen absorbed during welding.
2. To reduce the added cost associated with the welding procedure precautions for every bridge project, an effort should be undertaken to develop a nondestructive weld inspection procedure that can reliably detect the presence of hydrogen-induced microcracking.

The one-time cost of the enhanced AE system developed in this study is approximately $25,000. This system could be incorporated with VDOT's current procedures to ensure the quality of welded structural steel bridge elements. Quality assurance of welded steel elements prior to erection is critical. Crack detection and repair in service may cost on the order of hundreds of thousands of dollars, depending upon the severity of the crack and the criticality of the element to the bridge structure.

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FINAL CONTRACT REPORT

QUALITY ASSURANCE TESTING OF A HIGH PERFORMANCE STEEL BRIDGE IN VIRGINIA

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ABSTRACT

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INTRODUCTION

High performance steels (HPS) have been developed under a cooperative research effort involving the Federal Highway Administration (FHWA), the American Iron and Steel Institute (AISI), and the Department of the Navy (USN) and are now being used to fabricate steel bridge structures.[1,2] Although these HPS materials have the same strength level as AASHTO M270 steels, their chemical and physical properties allow more economical fabrication practices to be employed. A low carbon A709 Gr 70W steel processed via hot rolling and reheat quench and tempering was found to provide mechanical properties that met AASHTO requirements and exhibited characteristics that would enable a good weld. Assuming quality weld consumables are used, the low carbon levels and alloy concentrations suggest that sound welds may be obtained without preheating.

Problems with fabrication have been experienced during the first two projects to use HPS-70W in Tennessee and Nebraska. In both cases, "cold" or "delayed" cracking apparently due to hydrogen embrittlement was experienced. Some work[3] has been performed to determine the level of diffusible hydrogen in the welds and to determine the cause of cracking. Recently reported findings[4] suggest that the apparent cause of the high levels of hydrogen was inappropriate flux material. These reports, however, did not include any discussion as to whether the issue of cold or delayed cracking was considered. Experience in Virginia[5] suggests that delayed cracking can occur in a bridge structure even years after the initial fabrication and erection. To ensure that a structure made of HPS material is of good quality, it would seem that it is necessary to evaluate the base metal and weld materials and the performance of the final structure.

A structure was identified to be designed and built with HPS-70W steel., which was the first application of HPS-70W in Virginia. Documentation of the entire project from design through fabrication and erection seemed appropriate. In addition, an evaluation of the overall bridge performance under live load and long-term monitoring was necessary to develop the confidence necessary to allow for expanded use of HPS. Concerns continue to exist regarding the potential for delayed cracking to occur in the welds of fracture critical member fabricated from HPS. The effects of base metal properties, base metal hydrogen content, welding parameters, and weld consumables on the weld microstructure, diffusible hydrogen, and residual stresses are not clear.[6,7]

PURPOSE AND SCOPE

The objectives of the original study were to recommend appropriate procedures for welding the bridge members to assure quality welds, perform a comprehensive analysis of the metallurgy of the base and weld metal, conduct delayed cracking tests for all weld configurations, and to thoroughly evaluate the bridge members during fabrication and in the field with nondestructive evaluation (NDE). Critical areas on the girders were to be identified and instrumented for the purposes of long-term performance.

Due to the delays in construction and the increased experience nationwide using HPS70W, the objectives were modified to address new areas of concern. The new objective was to determine whether hydrogen-induced microcracking might occur and go undetected using the standard welding and weld inspection process.

Typically the effects of hydrogen on welded products are determined by a “constrained” specimen test where a test weld is made on a pair of members that have been attached to a rigid support. As the welded part cools and thermally contracts, stresses are induced triggering any absorbed hydrogen that may induce cracks. This test is considered severe and the cracking that occurs, if hydrogen is present, is quite evident by visual inspection.

During early fabrication of HPS70W bridge members welded procedure qualification record (PQR) specimens experienced cracking. This problem caused obvious concern and an extensive investigation into the cause was conducted. The problem was ultimately attributed to high levels of moisture in the weld flux. As a result extra precautions were specified for the choice of this consumable and few if any problems subsequently have been reported.

However, in that the original problem was easily detected by visual inspection a question exists regarding whether the lack of visible cracking is assurance that no hydrogen-induced cracking has occurred.

Acoustic emission (AE) monitoring uses very sensitive acoustic detection instrumentation to detect the sudden release of mechanical energy such as might result from microcracking in a steel member under stress. The observation of such AE subsequent to welding might then serve to alert the steel fabricator to the occurrence of hydrogen-induced microcracking even if cracking is not visible.

AE monitoring during welding fabrication requires special instrumentation because of the elevated temperatures and electromagnetic interference due to the welding process. As a result it was decided to not attempt to monitor AE during actual fabrication. Instead welded specimens cut from actual HPS 70W PQR plates were considered.

METHODS

To simulate the situation that occurs during welding the HPS70W specimens were subjected to a process that would introduce hydrogen and then these specimens were mechanically loaded. In this way the steel with hydrogen would be subjected to stress that is known to induce the embrittling effects and cause cracking. To study this phenomenon, it was necessary to load the steel specimens in manner that would not introduce spurious AE; this required modifying a dead weight loading machine. In addition, since AE has been detected during mechanical loading of steels without hydrogen it was necessary to ascertain the nature of the AE due to mechanical loading of HPS70W and the weld metal [of the bridge steels available A588 was selected as similar in properties to an under matched weld metal] apart from the effects of hydrogen.

In addition, since the hydrogen-induced macrocracking was observed to occur in a very short time interval, AE monitoring that would not miss the occurrence was performed.

To achieve the objective the following tasks were performed:

1. Establish an AE monitoring procedure to determine the nature of AE due to plasticity and crack growth for comparison with AE due to hydrogen-induced microcracking.

2. Establish a quiet mechanical loading system in order to make it possible to detect AE in as sensitive a manner as possible.

3. To allow for differentiation between hydrogen and non-hydrogen AE sources in the tests of specimens HPS70W, perform tests to document the non-hydrogen AE.

4. Conduct tests on HPS70W specimens exposed to hydrogen.

AE Monitoring Procedure

Conventional AE monitoring has over the years evolved from counting the voltage excursions above a threshold of signals detected by transducers, to recording such signals on high fidelity analog tape systems to the present day process where computer-based high speed digital data acquisition systems are used to record and analyze the data. Unfortunately such systems suffer a limitation with regard to continuously recording AE data. The limitation is due to the fact that these systems are designed to collect data at high speeds and save the data to a data buffer; this approach facilitates the high-speed acquisition. However, once the data buffer is filled the system stops collecting data for a “brief period” of time while the system transfers the data from the buffer to another storage device, typically a computer hard drive. If the process for which the AE is being monitored occurs over a large period of time, the time period missed during the accumulated brief periods writing to the hard disk may not result in important data being missed. However, if the process being monitored occurs over a short period of time, such as the hydrogen-induced cracking then the possibility that AE might be missed increases significantly.

To reduce the chances that AE would be missed, a system was assembled that allowed for AE to be collected for a short but significant time interval, approximately 1 second, while the mechanical loading of the steel specimens occurred. The system consisted of a high-speed analog to digital data acquisition board that digitized the AE data at 5MHz with a very large data buffer: 4 Mb.

The acquisition system was triggered using the signal from the loading system load cell in order to synchronize the loading and acquisition.

Mechanical Loading System

Trucks crossing bridges on rubber tires create a remarkably quiet mechanical loading system in the frequency range used for AE monitoring. A small section of welded plate once the welding has finished and begins to cool also produces a very quiet loading system as the contraction of the part is constrained. If the welded member is as large as a bridge girder, portions of the weld are cooling and subjected to stresses due to thermal contraction while other parts of the member are still being welded and the environment is acoustically noisy. In the laboratory typical hydraulic or screw driven testing machines are extremely noisy and make high fidelity detection of AE difficult. In this study to make it possible to detect AE in as sensitive a manner as possible a special quiet loading machine was used.

A dead weight loading machine, Figure 1, was modified to load the specimens and allow any deformation to occur without constraint. The machine normally used for creep has a lever arm actuator set at a 20:1 ratio. Hence on the "high" side a 2000 lb load on the specimen is accomplished with only 100 lb on the "low" side weight pan. The low side of the lever without weights added generates a 235 lb specimen preload. A pneumatic actuator with a 7-inch stroke, placed under the weight pan to lift the weights, accomplishes consistent loading and unloading of the specimen. The weight pan is hung from the lever arms with a steel cable loop so that when the weight pan is lifted up the preload remains on the specimen. To monitor the load on the specimen a miniature 15 kip load cell is installed on the high load side. Reduction of noise from the metal surfaces of the machine parts rubbing against each other is accomplished by applying rubber sheeting, Teflon, and vinyl tape where possible. Transmission of noise from the rest of the machine to the specimen is reduced or delayed by the complexity of the shapes of the components in the load line: turnbuckles, threaded rod, cable loops, etc. Repeated loading of the system at loads above those used during the actual testing are expected to reduce any AE from the loading system due to the Kaiser effect. [The Kaiser effect, named after Josef Kaiser, describes the phenomenon where no significant AE occurs during reloading of a structure until after the highest previous load level is exceeded.]

Specimen loads are monitored using the in-line load cell. Tests were run with a dummy specimen and several appropriate different loads to characterize the behavior of the loading mechanism. It is important to note that because there is very little damping in the system elasticity allows vibration to occur at the upper load levels. This is because the hydraulic actuator retracts from the weight pan rapidly enough that the momentum of the pan causes the arm to deflect beyond the static equilibrium position and a vibration occurs due to the elasticity of this load line. Typical load profiles are shown in Figure 2. The load cell signal is also monitored and used to trigger the data acquisition.

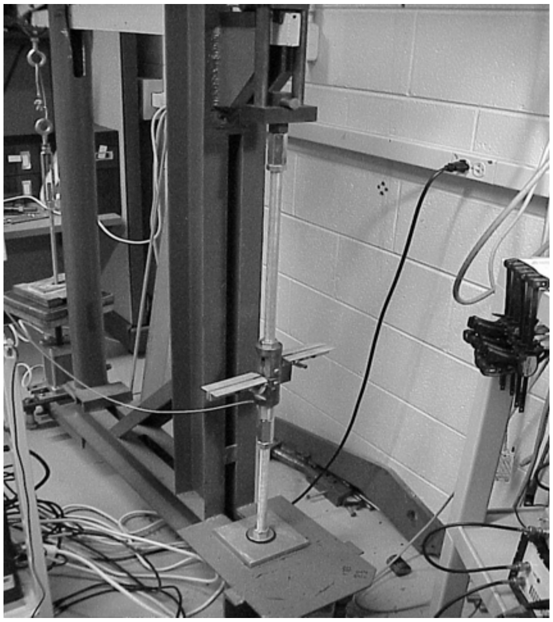


Figure 1. Pictures of the modified dead weight loading system: in the foreground of the image on the left, the specimen gripping fixture can be seen. In the image on the right, the lower portion of the hydraulic weight support unit can be seen beneath some dead weights.

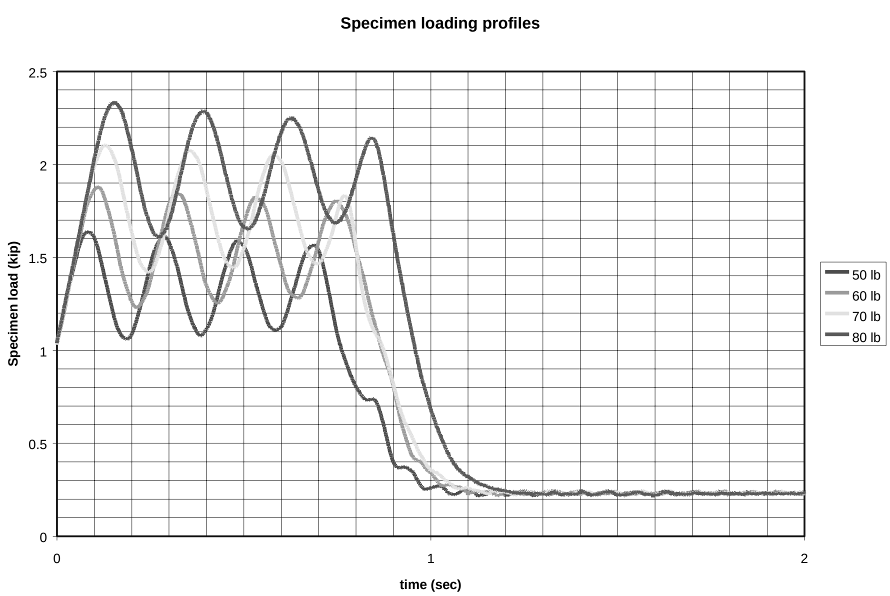


Figure 2. Plots of the load variation for loads on the weight pan of 50, 60, 70, and 80 lb.

Specimen Design

Tests were performed on crack opening displacement (COD) specimens to quantify the nature of AE from A588 [chosen for its similarity to the HPS70W weld metal] and HPS70W.

These specimens were initially loaded, then precracked in an MTS hydraulic testing machine prior to being reloaded in the dead weight load machine. This process was used to determine the nature of AE from preexisting cracks in these steels as well as emission from elastic loading. Since microstructural features may cause plasticity on a microscopic scale when loads are applied it was expected that AE from plastic zone formation would also be of interest. Consequently, loading was performed that would cause the formation of a plastic zone at the tip of the precrack and AE monitored. The nature of the crack extension and the plastic zone formation were documented using Normarski metallography.

Despite the fact that AE monitoring has been applied in numerous studies to detect and track crack growth little if any conclusive evidence has been published to establish whether crack extension is a source of AE. What is indeed well established is that in field-testing crushing of debris and corrosion product will cause AE from cracks. Because of the location of the source, the location of the crack can readily be determined using triangulation with AE monitoring. While in some instance differentiating between whether AE is associated with crack extension or plastic zone formation may be merely an academic exercise, in instance where low-level cyclic loading is mingled with high load overloads it is important.

Work by Miller and Pursey[8] has suggested that cracking will emit a significant amount of energy in the surface wave mode. In order to take advantage of this feature and to optimize sensitivity to such modes a modified crack opening displacement specimen was designed, Figure 3. The modification involved providing an extended portion to accommodate a National Institute of Standards and Technology (NIST) point AE transducer. Because of the design of the transducer it is necessary to orient the transducer so that it sets on the surface. However, the transducer, despite the restrictions on how it can be attached, has an output that has been shown to be directly proportional to the out-of-plane displacement of the surface due to AE. Consequently using this type of transducer at both of the positions indicated by the arrows in Figure 3, allows the AE signal output to be related to out-of-plane displacements caused by various different wave modes.

The thicknesses for the specimens do not follow ASTM E399 that specifies that the ratio of width (the 2.00 in dimension) to thickness should be in the range of 2 to 4, preferably 2. The thickness determines the state of triaxiality for the stresses at the tip. The thickness to ensure plane strain conditions is determined by procedures noted in ASTM E399, which also specifies that all other dimensions are functions of the thickness. The smaller thickness was used here so the triaxiality would not be the most severe possible since not all bridge applications are plane strain.

As is generally the case with AE monitoring of laboratory specimens that are small compared to a bridge structure, the nature of the AE detected is dominated by geometric or structural resonances. This may be seen in Figure 5, introduced later, that displays the output signal from each of the NIST transducers caused by breaking a short segment of 0.3 mm pencil lead on the face of the specimen near the edge of the crack tip.

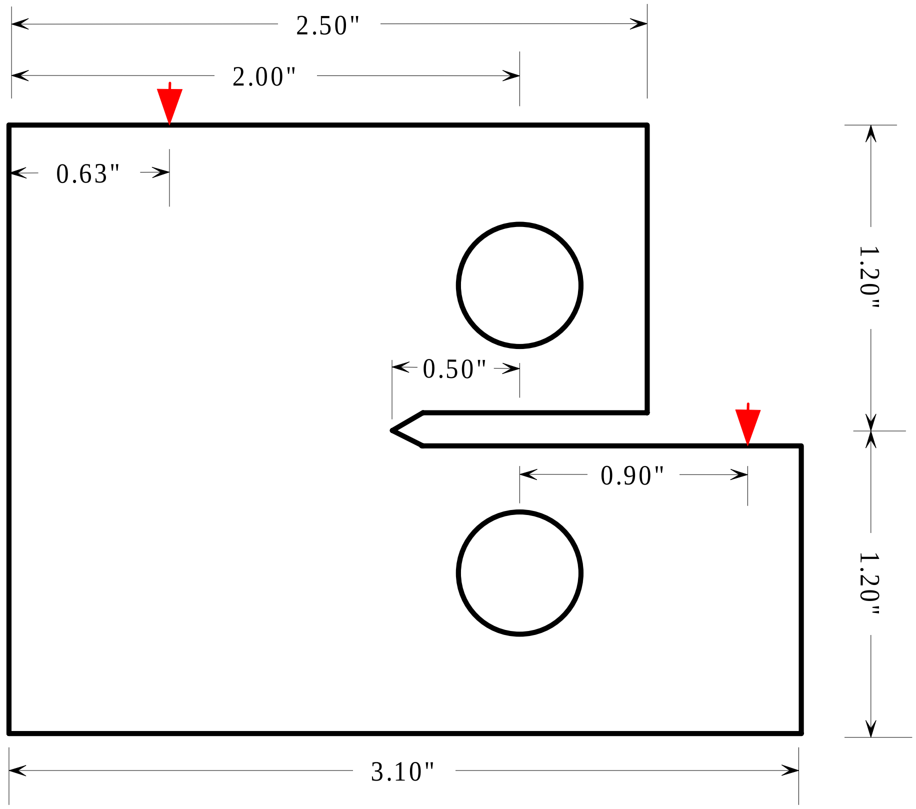


Figure 3. Modified ASTM E399 compact tensile specimen profile of the 0.25" thick specimens with general dimensions. The arrows indicate the locations where NIST Transducers were placed for AE monitoring. The extended lip was provided so as to allow for one of the NIST transducers to be on the surface of one of the "crack faces" in order to increase the chances that Rayleigh surface wave modes are detected.{See ASTM E399 for more details. [Note that the 0.75" thick specimens follow the ASTM E399 profile more closely and do not have the 3.10-in extended section.] The thickness for the specimens does not follow E399 that specifies that the ratio of width (the 2.00-in dimension) to thickness should be in the range of 2 to 4, preferably 2. The thickness determines stress triaxiality at the tip. The thickness to ensure plane strain conditions is determined by procedures noted in ASTM E399, which also specifies that all other dimensions are functions of the thickness. A smaller thickness was used to consider a situation less severe than plane strain.}

AE from Non-hydrogen Sources

To allow for differentiation between hydrogen and non-hydrogen AE sources in the tests of specimens HPS70W tests were performed to thoroughly document the non-hydrogen AE. Various loading regimes that caused elastic, plastic, and crack extension were considered. The primary focus of the effort was directed at specimens that contained sharp cracks, since AE from hydrogen-induced microcracking might be mingled with AE from growth of these microcracks or localized plastic zone formation due to the presence of the hydrogen-induced microcracks.

Because the issue of hydrogen embrittlement was intimately related to the regions that were fabricated by welding, consideration was given to detecting AE from HPS70W base metal and from metal that might behave in a fashion similar to the weld metal; A588 was select as representative of the weld metal.

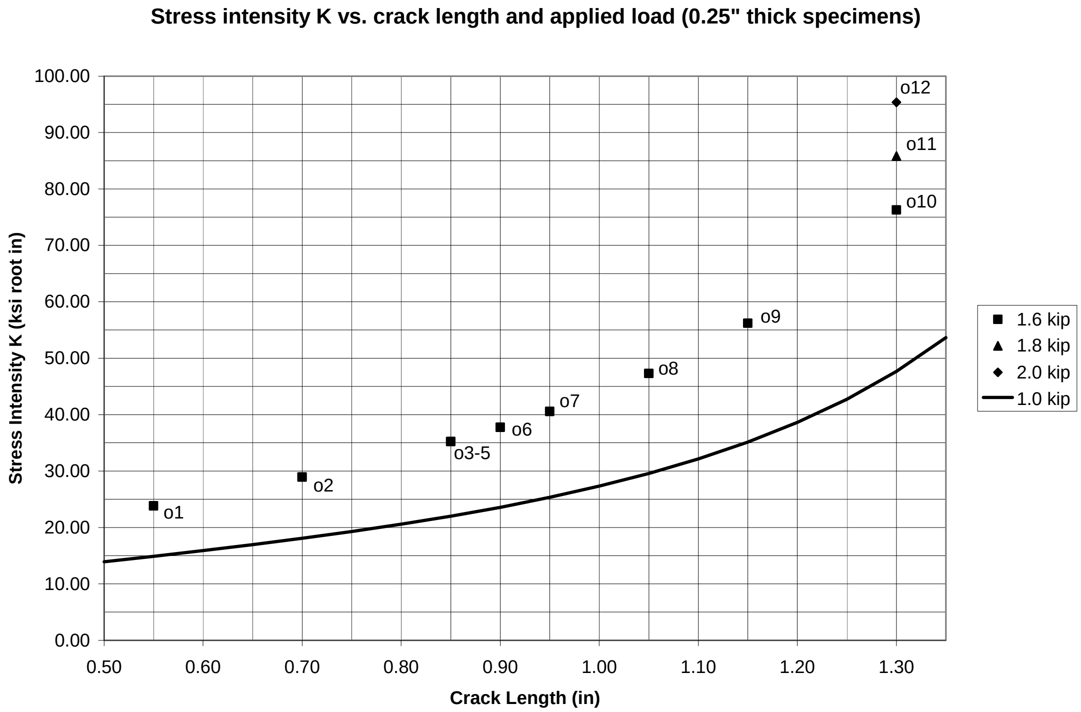
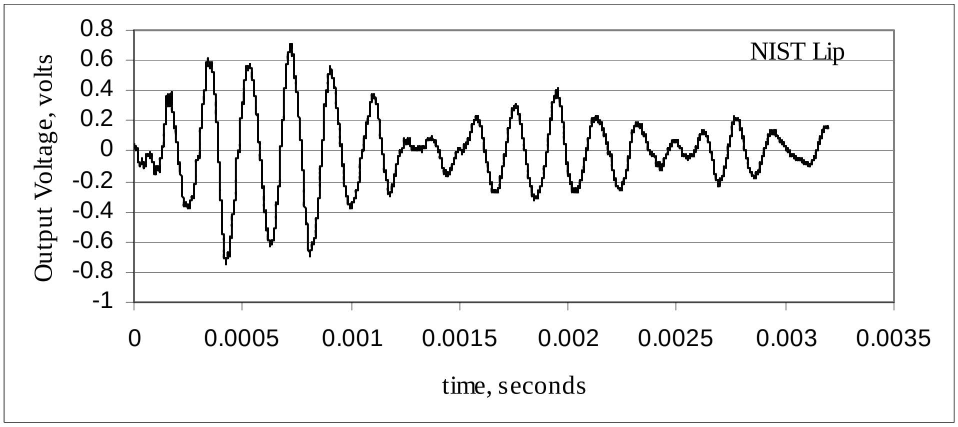


Figure 4. Stress intensity progression during load regime of the 0.25 in thick, polished specimens. The machined notch was extended, and the subsequent crack growth accomplished by cyclic loading between 50 and 1000 lb. The 1.0 kip curve shows the maximum stress intensity for that regime. The individual points show the stress intensity due to the overloads during which AE was monitored. Note that overloads 3, 4, and 5 were carried out at approximately the same crack length with only 1000 cycles [50-1000 lb] used to "sharpen" the crack tip between these overloads; no measurable crack extension was observed. Overloads 10-12 were also conducted at approximately the same crack length with 50 cycles [50-1000 lb] to sharpen the crack tip, except between 10 and 11 where 100 cycles were added.

The specimens were subjected to cyclic loading between 50 and 1000 lb in the MTS loading machine; the 50 lb load was used to avoid issues related to specimen and loading pins repositioning if the load were reduced all the way to zero, so essential the cycling was R = 0. The extension of the crack was monitored by stereo-microscopic observation facilitated by strobe lighting during the cycling. Extensive documentation was made of the crack extension and the associated plastic zone formation.

Periodically the specimens with a sharp crack tip were removed from the MTS hydraulic load frame and placed in the previously described quiet loading machine and subjected to an overload. AE was monitored during the overloads, and near the final overloads, when small numbers of load cycles were used to sharpen the notch without significant crack extension AE was even monitored during these load cycles. Figure 4 provides an overview of the stress intensity for each of the overloads as well as associated crack length.



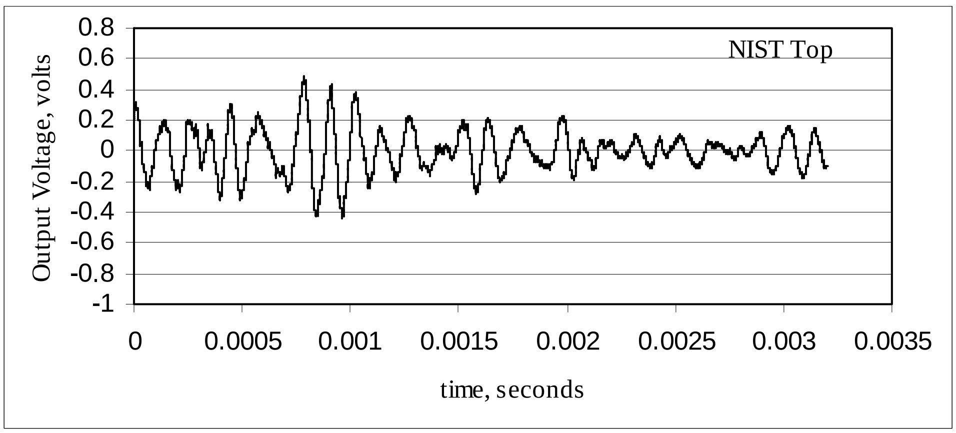


Figure 5. a) Output voltage versus time due to a pencil lead break near the notch tip for a NIST pointducer located on the lip, b) Output voltage versus time due to a pencil lead break near the notch tip for a NIST pointducer located on the top (see Figure 3).

AE was collected during the overloading with NIST transducers to provide for a means of signal characterization. The records were recorded simultaneously, but because of the different transducer locations they detect different modes of wave propagation at different time with respect to the occurrence of an AE event. Figure 5 shows the records produced by a pencil lead break simulated AE source located at the specimen notch tip.

AE from HPS70W Specimens Exposed to Hydrogen

Finally, thick specimens fabricated from actual PQR weld plates where the notch was placed at the heat affect zone, and thin specimens with the notch in the weld metal that were charged with hydrogen were tested. Thick specimens were used to try to expose a large volume of material in the notch region to hydrogen in order to increase the probability of hydrogen-induced cracking that might serve as the source of AE.

The pinholes of each of the thick specimens were first loaded to lessen the possibility that AE would be created in these highly loaded areas during the loading of the specimens. Each specimen was then loaded to a load that was not expected to cause the notch to extend. AE was monitored. A set of specimens was then subjected to a zinc-plating process including an acid precleaning step [10 minutes in hydrochloric acid] and the plating step [plated to 0.0005 in. or 0.001 in.] that were altered to increase the amount of hydrogen absorbed by the HPS70W material. Typically properly zinc plated parts are baked for several hours at 400^{o}F to drive off any hydrogen absorbed during the plating process. One plated specimen was baked to drive off any hydrogen and then reloaded while monitoring AE to determine if the zinc plating emitted significant AE. The other specimens were then reloaded while monitoring AE when this test suggested loading the zinc-plated specimen emitted no significant AE.

Specimens were loaded initially to obtain the baseline AE due to any system noise or AE from deformation mechanisms. The series of tests performed on both HPS70W and A588 specimens, and work by numerous researchers, indicated that AE would occur in steel from even nominally elastic loading. However, the principal reason for the initial loading of each of these specimens was to take advantage of the Kaiser Effect.

Subsequent to hydrogen charging the specimens were again loaded while AE was monitored. Then in almost every instance the specimens were unloaded and reloaded to determine if the Kaiser Effect was observed, for any new AE sources. It should be noted that the specimens are loaded by means of pins. While these pinholes were preloaded, the plating process involves an etching process that will remove a small amount of material. That and the fact that precisely relocating the hardened pins in the pinholes is not possible, argue that some new AE from the pinholes is possible. While the procedure for recording the AE waveform allows for detecting AE sources that emit different waveforms, specimen resonances were expected to dominate the waveform spectra. Consequently the presence of more AE was expected to indicate the occurrence of hydrogen microcracking, consistent with the behavior reported by other investigators.[9]

RESULTS AND DISCUSSION

Figure 6 is an example of an AE record collected from one of the transducers during an overload. As was mentioned previously this AE monitoring procedure was utilized in order to collect essentially all of the AE since it was not possible a priori to determine at what point AE due to various mechanisms would occur. While AE monitoring performed using parametric analysis allows for processing large amounts of AE over extended periods of time it is ill suited for identifying the source of the AE processed.

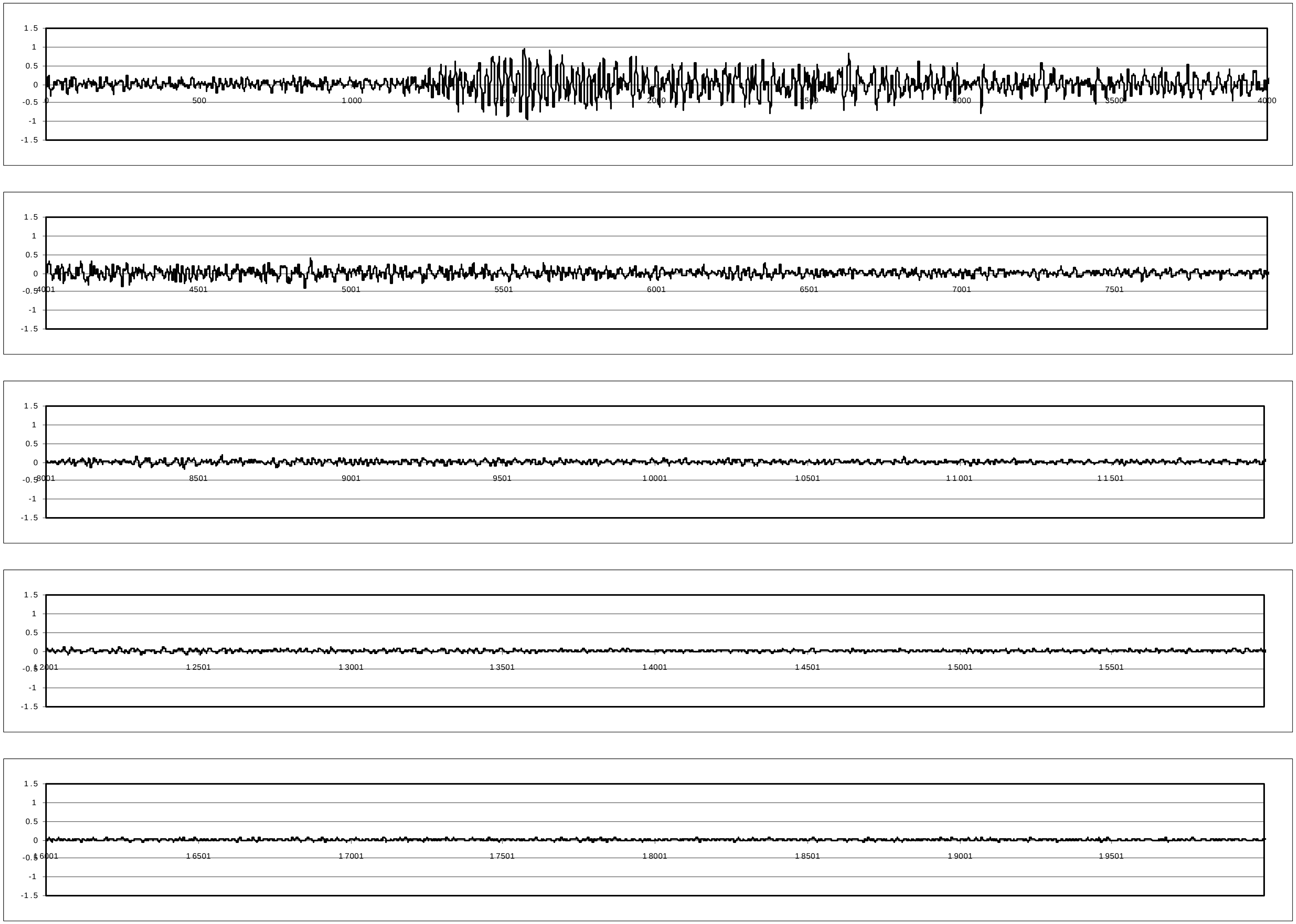
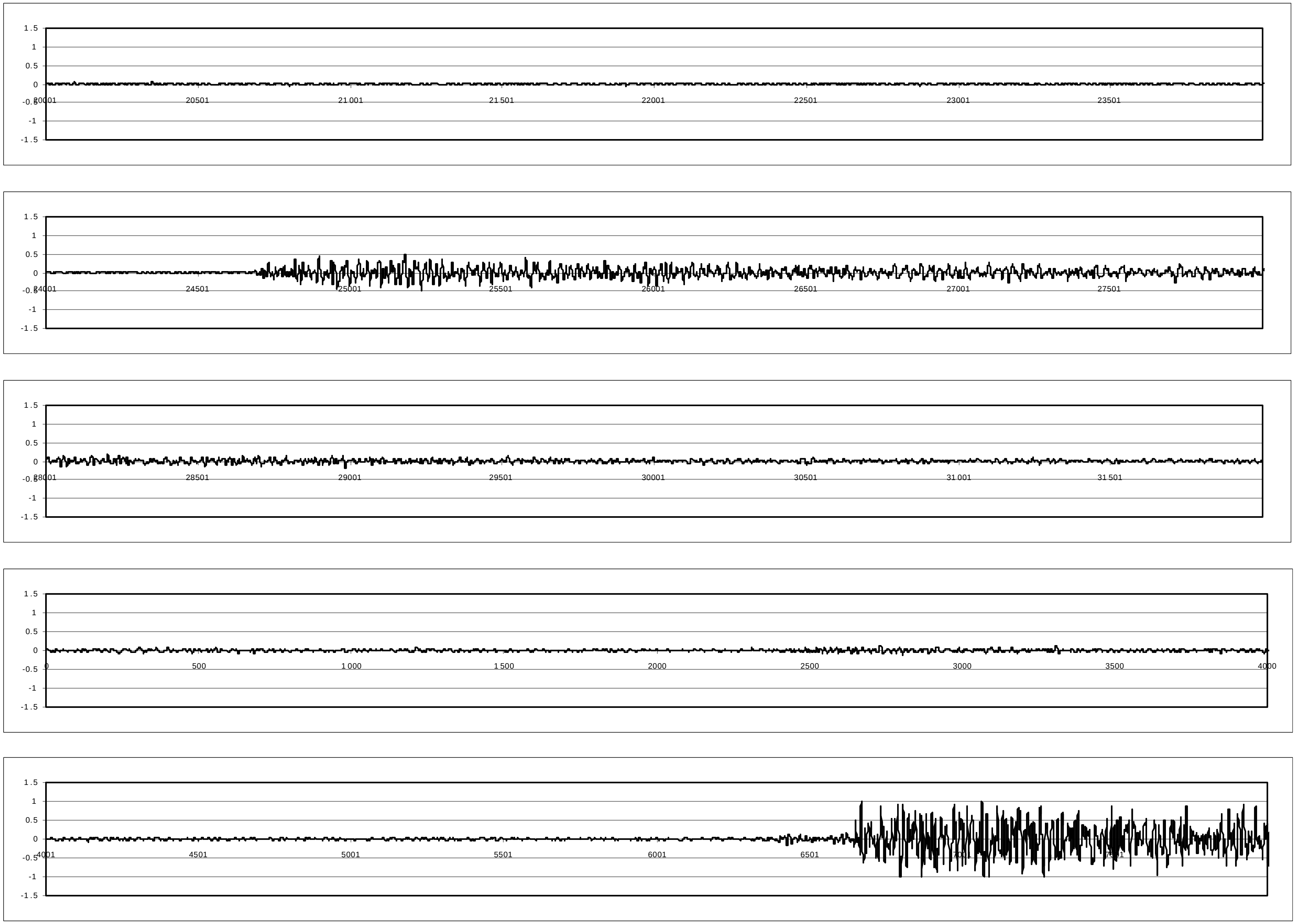


Figure 6



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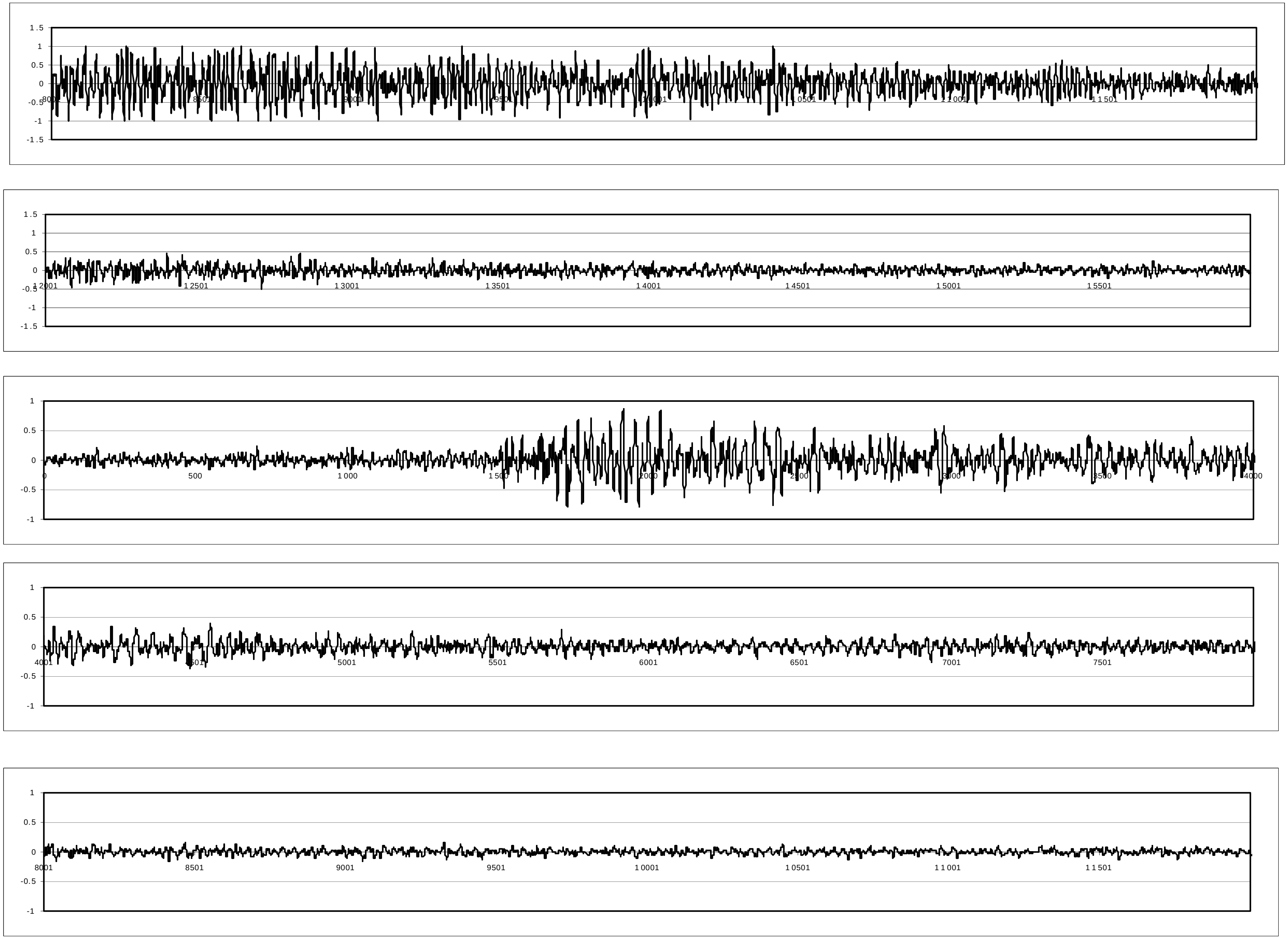

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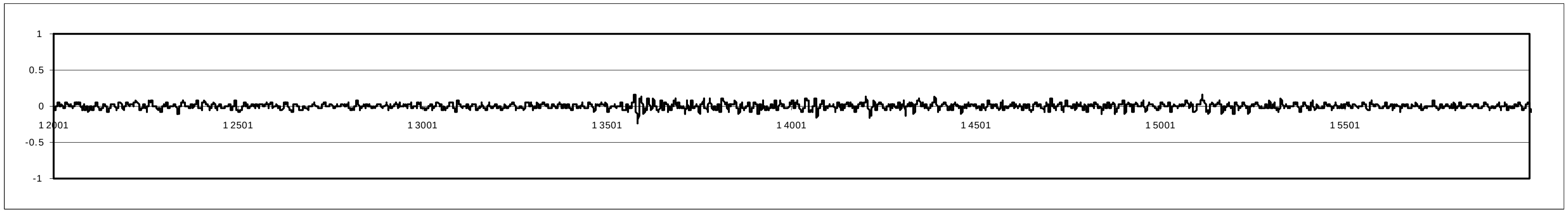


Figure 6. This sequence of graphs shows the record of the AE from one of the two transducers used to monitor the loading of an hydrogen charged HPS70W specimen. The data were collected at 5MHZ, so each point is separated in time by 0.5 microseconds. Each graph displays a time segment of 2 milliseconds. Data collection starts when the load reaches 1000 lb, and continues until the memory is filled, producing a record length approximately 1 seconds.

It is important to note that if hydrogen-induced microcracking were known to have occurred, then weld repair would most likely be undertaken in the fabrication shop. At present there have been some claims of success in detecting hydrogen-induced cracking by AE monitoring during weld monitoring. In this study the basis for requiring such monitoring, at considerable added expense, during fabrication did not exist. First, accepted practice at present deems that if PQR plates are found acceptable then the welding procedure is qualified for fabrication. If subsequent problems with weld consumables occur that would result in poor welds during fabrication the assumption is that these problems would be manifest as macrocracking of the weld. The question as to whether microcracking might occur and elude detection until after macrocracks formed in-service was the concern of this program. Second, if microcracking was suspected it is unproven that conventional weld inspection can detect such defects. Consequently alternative detection methods would be needed. AE monitoring of subtle forms of damage initiation and damage development have been demonstrated. In addition, as was referenced previously AE due to hydrogen-induced cracking has been detected during its formation. However, no work has been done to show that AE can be used to detect microcracks that have already formed. The logic of the approach used in this study was to first create and detect the formation of hydrogen-induced microcracks and then determine if cyclic loading of the members containing the already present microcracks would produce detectable AE. Such AE might result from either crack face interaction or growth of the microcracks. Consequently the preliminary portion of this study regarding AE from crack development is quite relevant to the ultimate objective; should microcracking due to hydrogen embrittlement or some other mechanism be present.

The present state of the art with regard to rapidly processing large AE waveform records is quite limited. Regions of the larger record must be identified by extraordinary signal amplitude, distinctly different spectral content, or some other means such as a record of strain or load in which specific features such as maxima or minima are noted. Once identified subsequent waveform analysis using various transforms such as Fast-Fourier Transform or Wavelet analysis are used to extract features that can be associated with different AE mechanisms. Because the transducer output in this study can be interpreted as out-of-plane surface displacements an attempt has also been made to interpret these displacements in terms of various deformation mechanisms anticipated to be active at the crack tip.

In order to associate the AE activity with material deformation or cracking for each specimen, images of the crack were recorded. Techniques designed to facilitate observation of the plastic zone formation and crack branching were used. A typical image for an HPS70W specimen for each of the 12 overloads is shown in Figure 7. Three magnifications are provided to allow for examination of direction of crack extension, crack face roughness, and crack tip branching. A corresponding image for an A588 specimen is shown in Figure 8. A complete set of images for both specimens is available from the authors. In both cases, the low load cycle crack growth, subsequent to early overloads, advanced the crack beyond the visually apparent plastic zone. This was not the case for the later overloads.

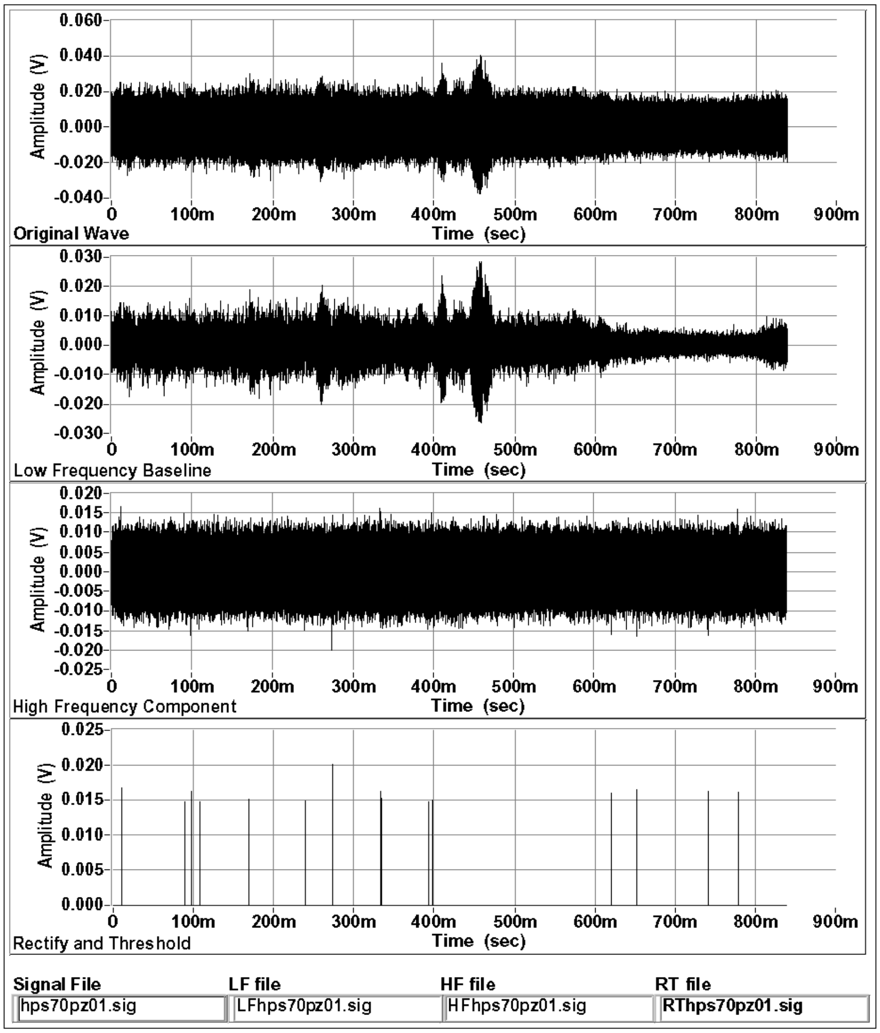


Figure 7. A typical image of AE activity for an HPS70W sample

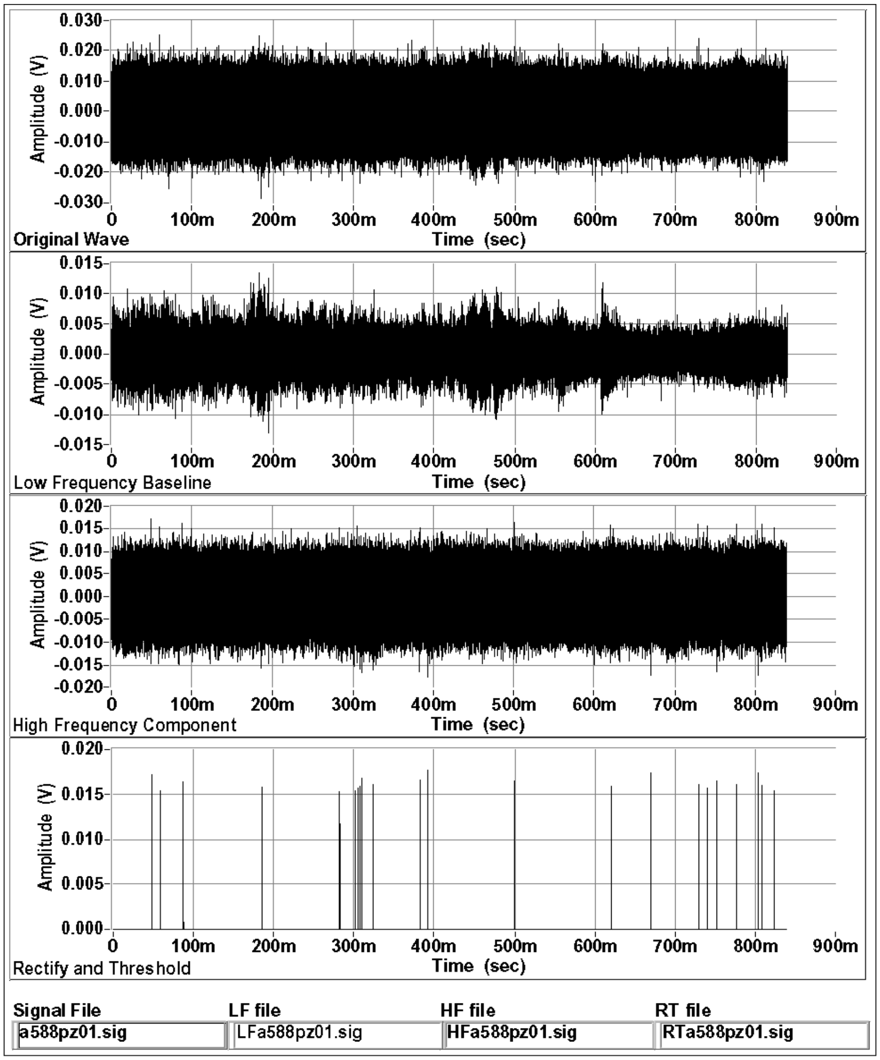


Figure 8. A typical image of AE activity for an A588 sample

Figure 9 and Figure 10 are images that show the rather large plastic zones formed by the latter overloads. It appears that low load cycling in the presence of a large plastic zone is associated with considerable meandering of the crack front as well as side branching. When the plastic zone is small the low load cycling of the crack seems to more directly advance the crack. This observation is significant for procedures that attempt to use AE or other methods that are related to formation or presence of crack surface. With regard to AE monitoring of crack advance, the additional crack surface formation would introduce uncertainty into the crack advance predictions. For bridge structures, overloads, anticipated to be caused by either heavily loaded or illegally overload trucks, the subsequent low load cycling, or high load cycling from other trucks will strongly influence the details of the crack front advance. The details of the bridge traffic are to some extent recorded in the fracture surface of the advancing crack.

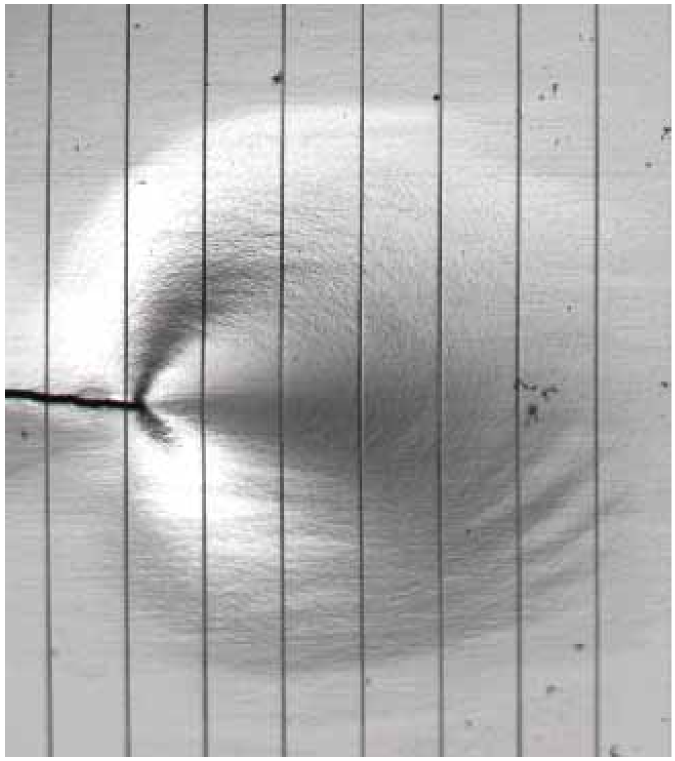


Figure 9a). Image of the plastic zone surrounding the crack for an HPS 70W specimen following the eleventh overload.

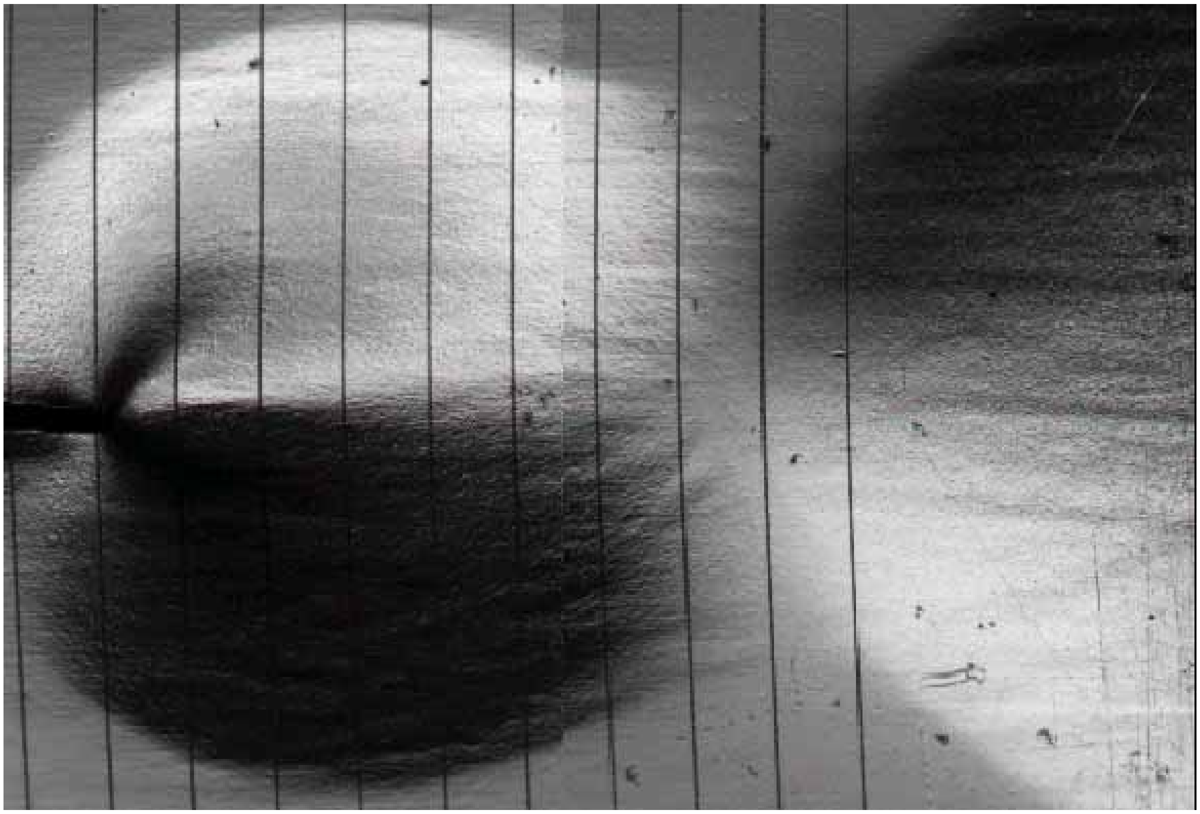


Figure 9b. Image of the plastic zone surrounding the crack for an HPS 70W specimen following the twelfth overload shown at the same magnification as 9a); two images have been overlapped to show the entire zone at this magnification.

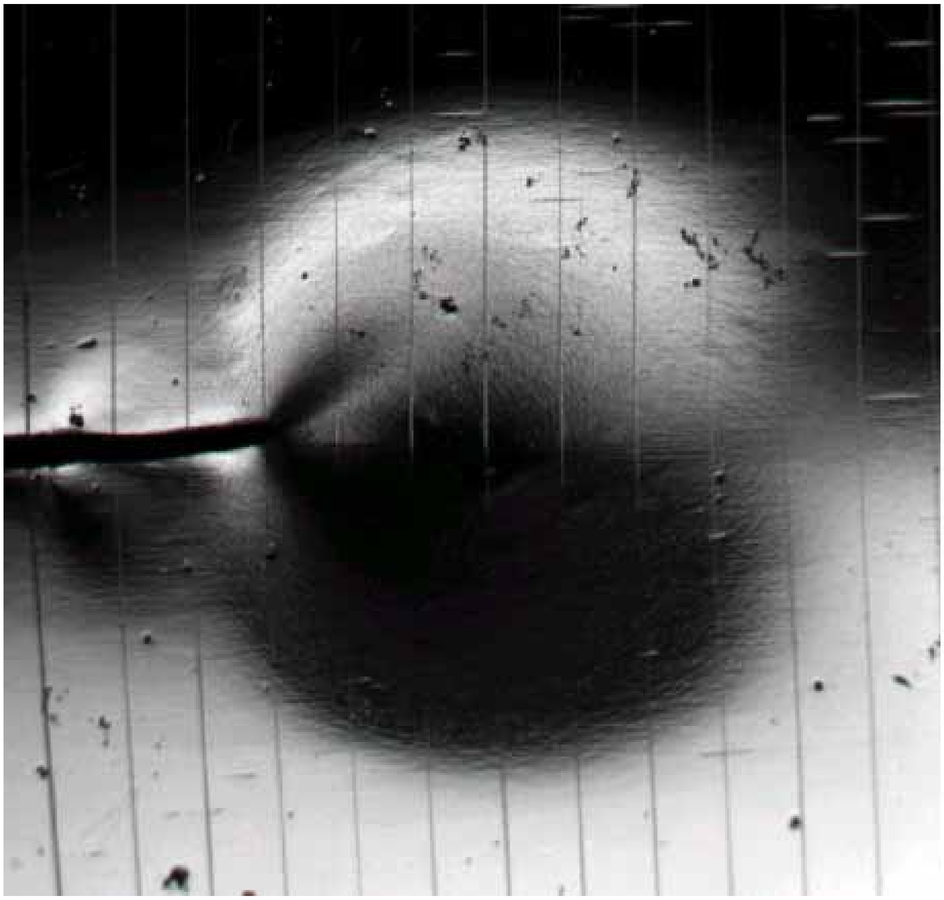
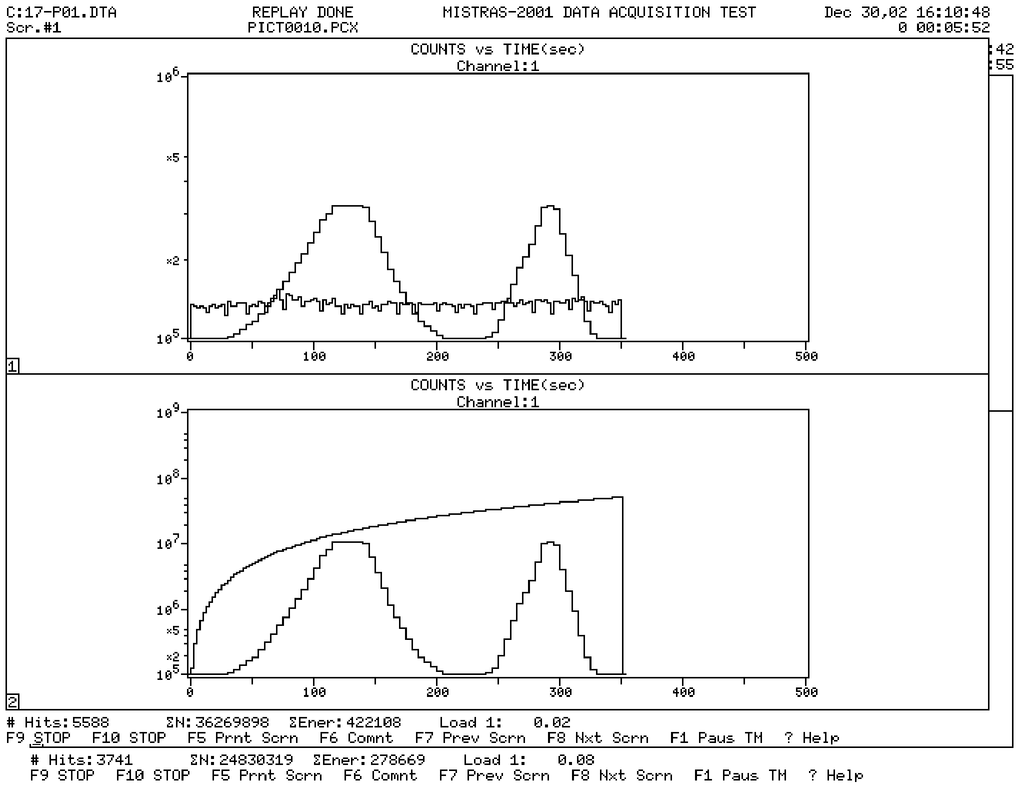


Figure 10. Image of the plastic zone for an A588 specimen following the eleventh overload.

Figures 11-13 display the overall record of AE collected using the Physical Acoustic System for three specific thick specimens: specimen 10 where the notch was located in the base metal and specimens 16 and 17 where the notches were located in the heat affected zone (HAZ) region of the welded plate. Evidence of similar significant AE is observed during the initial loadings, however, no significant AE is observed during reloading that is not believe to be associated with loading noise.

Figures 14-18 depicted the amplitude distribution for several different thick HPS70W specimens. Experience suggests that AE from similar specimens will exhibit some differences, so overall trends rather than individual details need to be considered. Numerous other specimens, 18 in all, were tested before plating, after plating, and after baking with similar behavior. The reader is reminded that in each figure the low amplitudes comprise the largest portion and larger amplitudes are essentially not present, indicative of little or no AE activity.



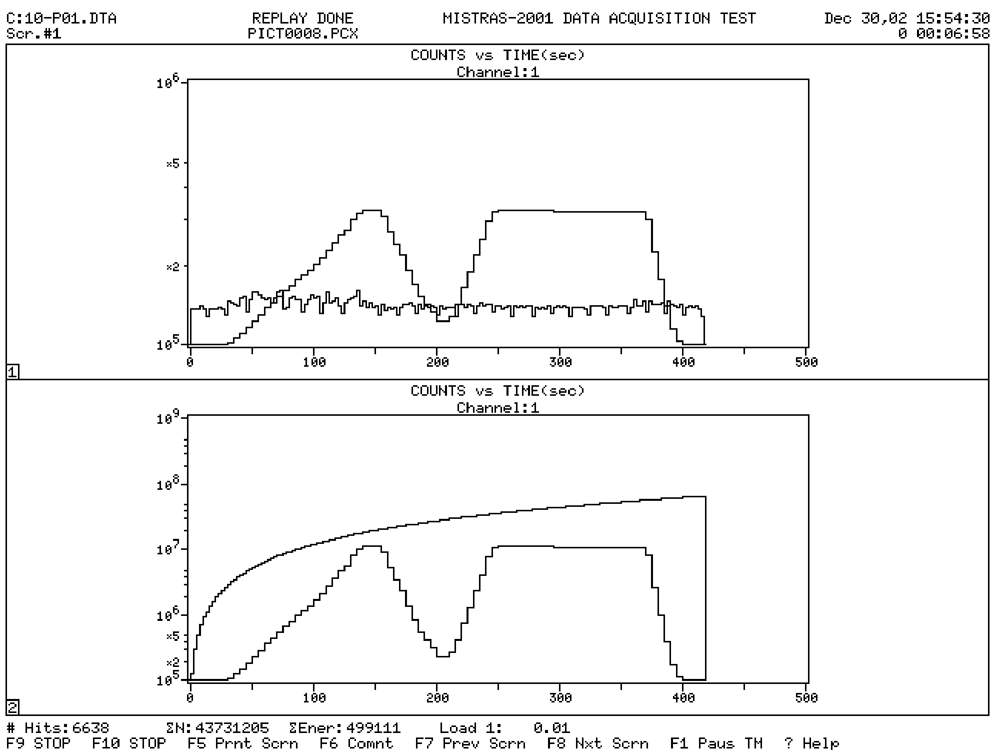
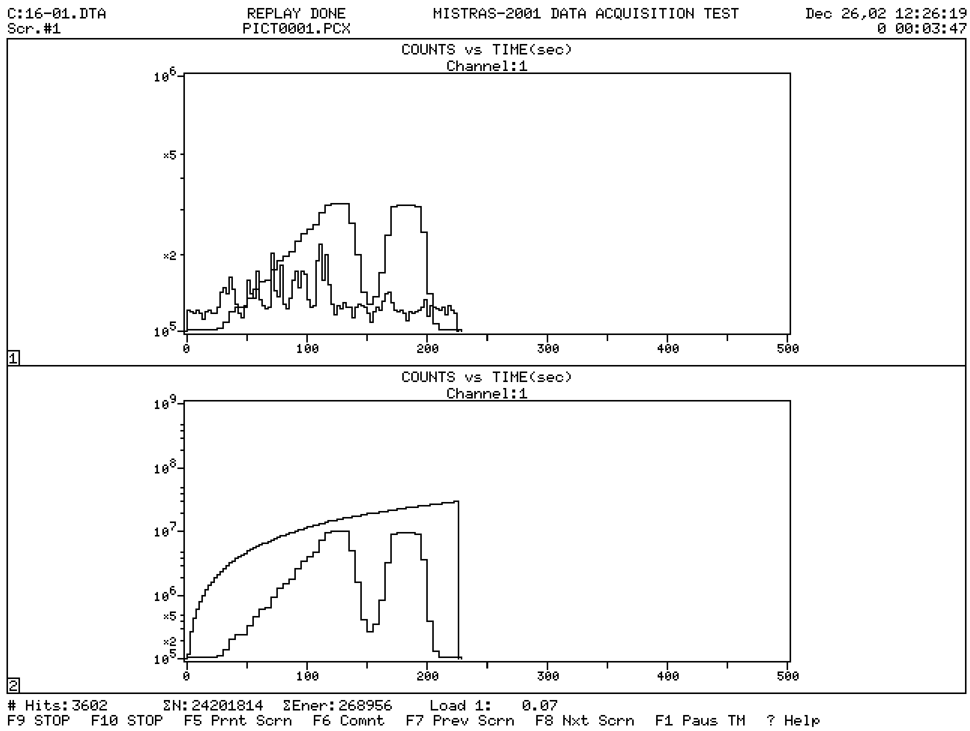


Figure 11 (top) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 10 (base metal); full-scale load corresponds to 2000 lb (bottom) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 10 after plating; full-scale load corresponds to 2000 lb.



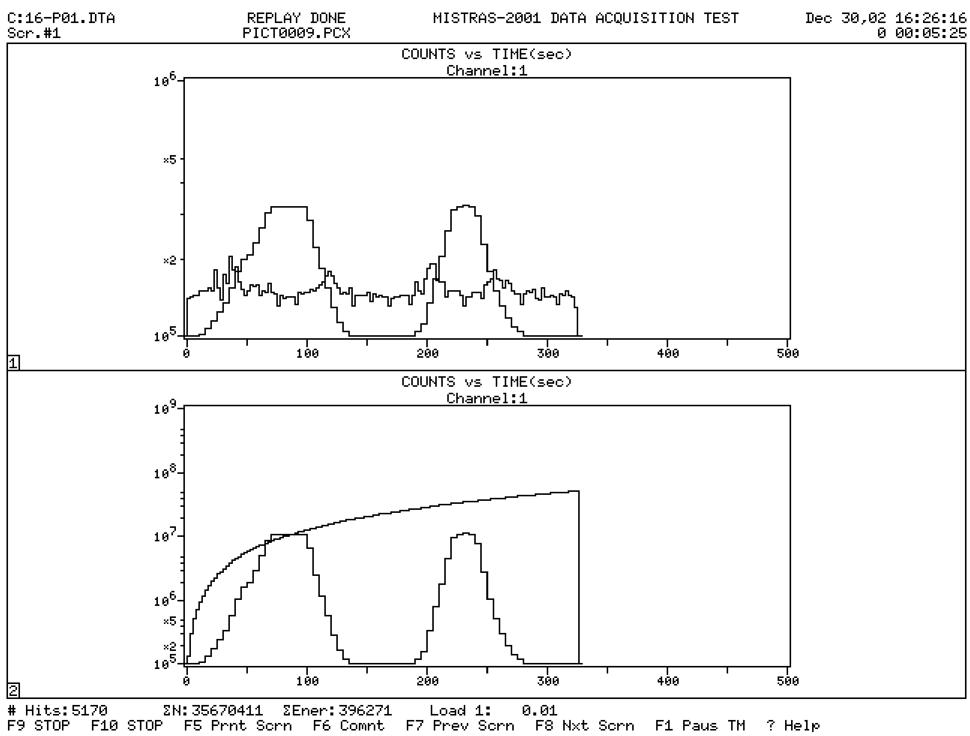


Figure 12 (top) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 16 (weld HAZ)); full-scale load corresponds to 2000 lb (bottom) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 16 after plating; full-scale load corresponds to 2000 lb.

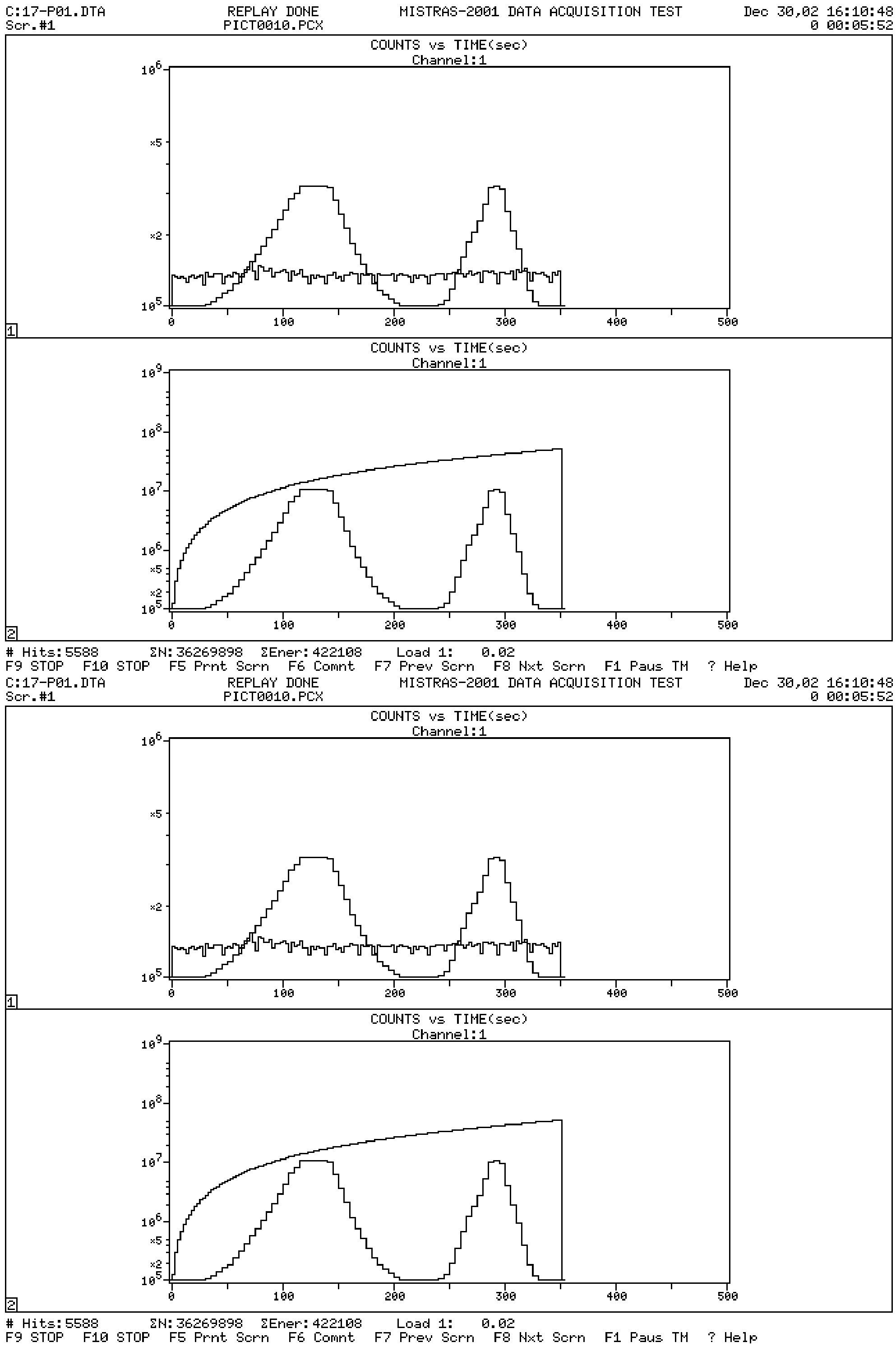


Figure 13 (top) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 17 (weld HAZ); full-scale load corresponds to 2000 lb (bottom) AE activity versus time and Summation of AE versus time, with Load versus time superimposed for thick specimen 17 after plating; full-scale load corresponds to 2000 lb.

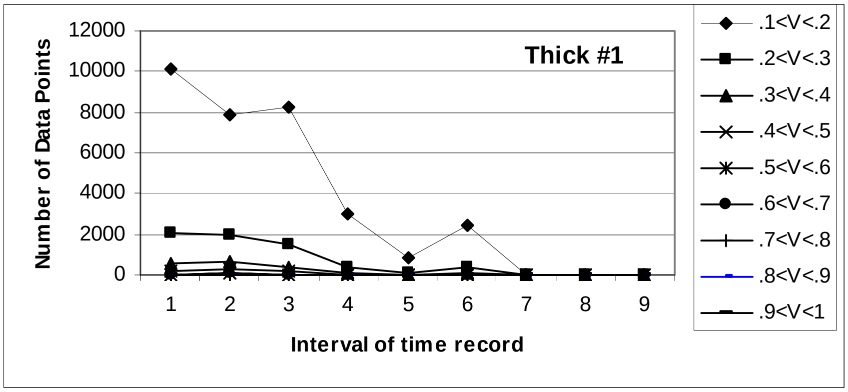


Figure 14. Family of curves showing the distribution of amplitudes over the loading period for thick specimen 1.

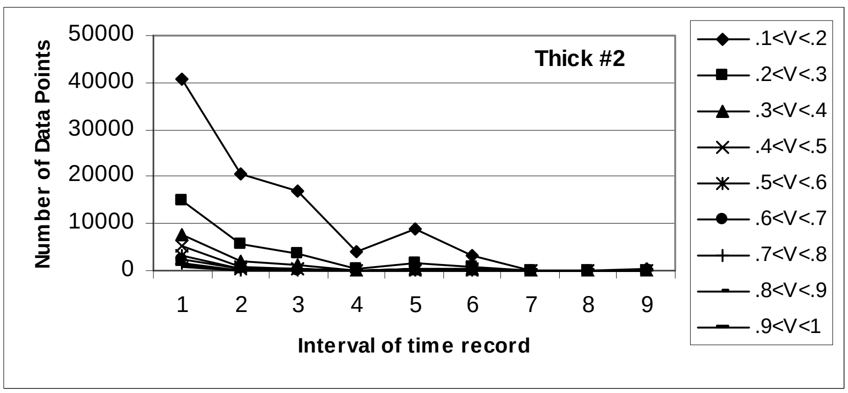


Figure 15. Family of curves showing the distribution of amplitudes over the loading period for thick specimen 2.

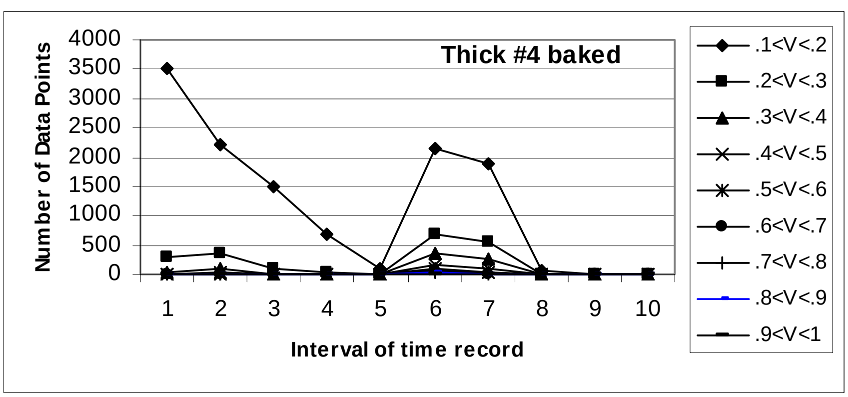


Figure 16. Family of curves showing the distribution of amplitudes over the loading period for thick specimen 4, baked for 2 hours at 400^{o}F.

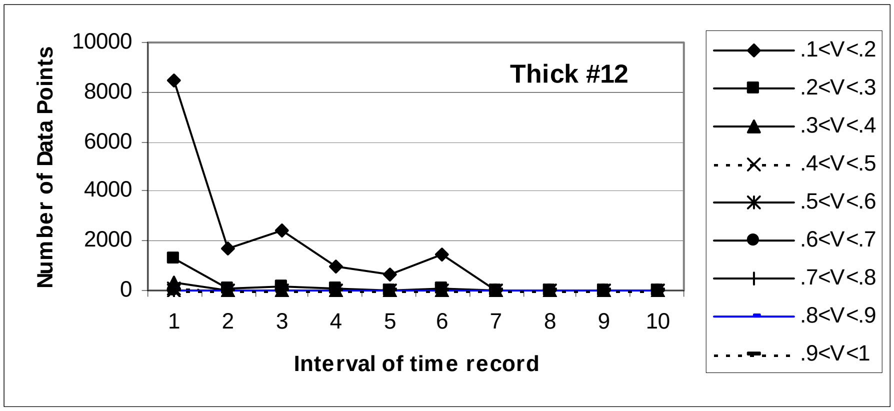


Figure 17. Family of curves showing the distribution of amplitudes over the loading period for thick specimen 12.

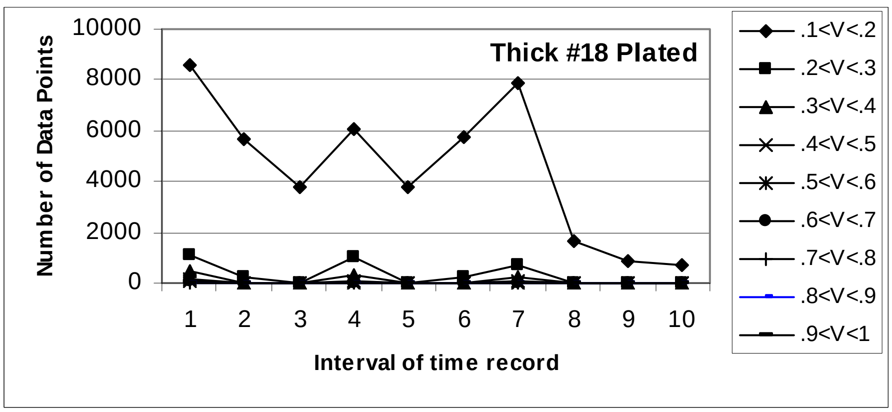


Figure 18. Family of curves showing the distribution of amplitudes over the loading period for specimen 5

AE From Slow Continuous Loading

Despite numerous different attempts to induce cracking due to hydrogen resulting from zinc plating using the drop loading with complete AE recording procedure described, no apparent hydrogen-related AE was identified. In a final attempt to produce such cracking the loading system was modified to allow for slow continuous loading at a rate of approximately 1 lb/sec. This modification was found to produce an essentially noiseless loading process, as evidenced by the fact that no AE was detected from the reloading of a thin specimen subsequent to initial loading and plating. Figure 19 shows the three polished thin HPS70W specimens where the location of the notch with respect to the weld metal is visible.

Figures 20 through 22 show the AE records for three thin specimens during the initial loading and then during reloading following the HCl acid precleaning, Zn plating process used to introduce hydrogen. These data were obtained using a Physical Acoustics Corporation AEDSP board and a wideband differential AE transducer along with the signal from the in-line load measuring device input as a parameter. In addition, more than two thousand individual AE waveforms were also collected and analyzed with regard to spectral content, amplitude, and the appearance of multiple closely spaced emissions. The amount of AE during the reload was remarkably small, even had not hydrogen-induced microcracking been anticipated. In fact of the 2000 waveforms collected, only 57 were collected in total during the reloading of the three Zn plated thin specimens. This has been interpreted as meaning that no hydrogen-induced microcracking occurred, and certainly no increase in AE activity due to any mechanism was observed.

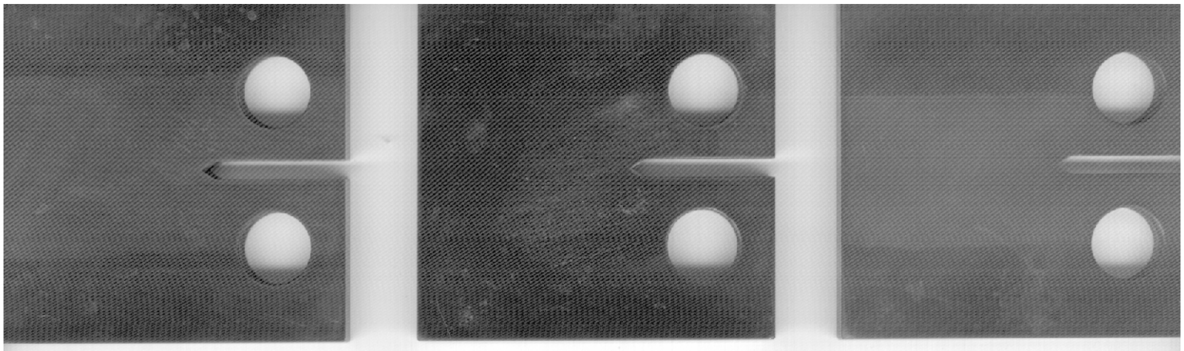


Figure 19. Images of three thin HPS70W [due to limited material no lip was included] where the central welded region is visible due to slight difference in coloration of the surface.

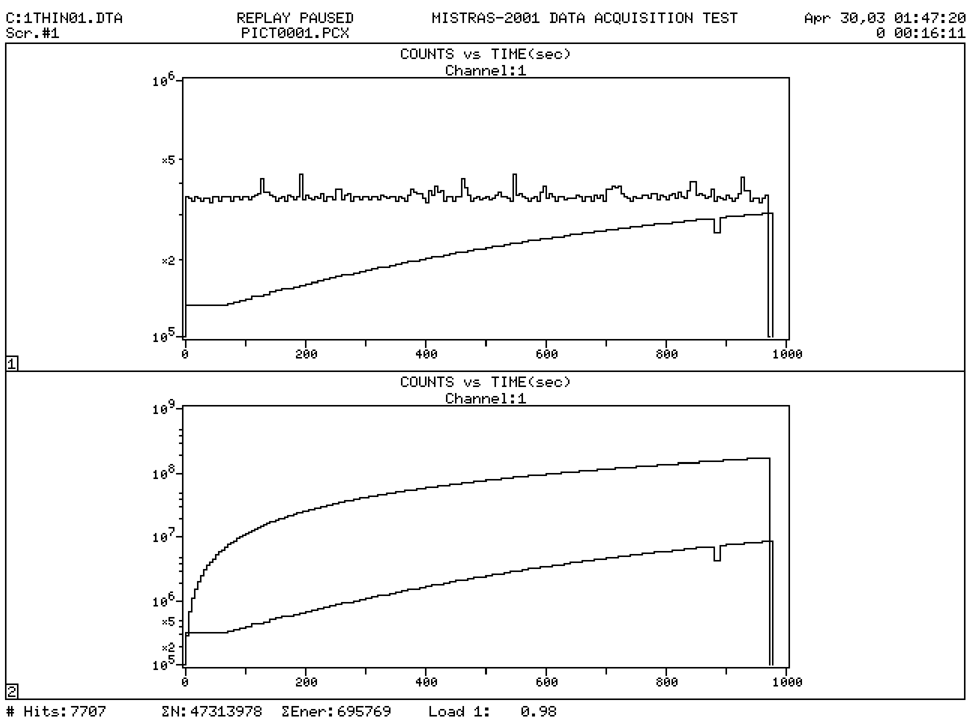


Figure 20a. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during the initial loading. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

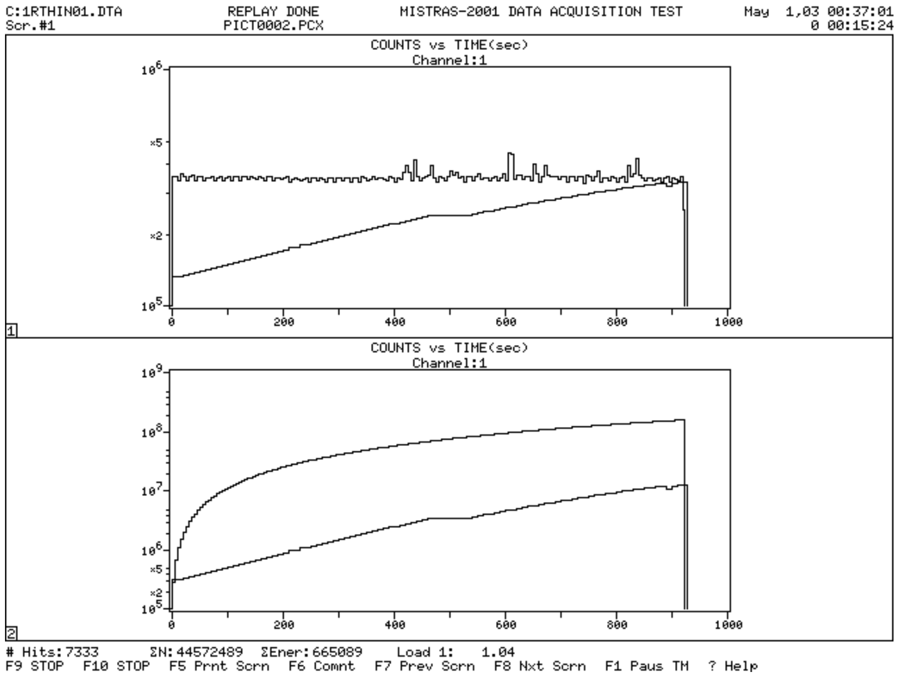


Figure 20b. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during a reloading following Zn plating. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

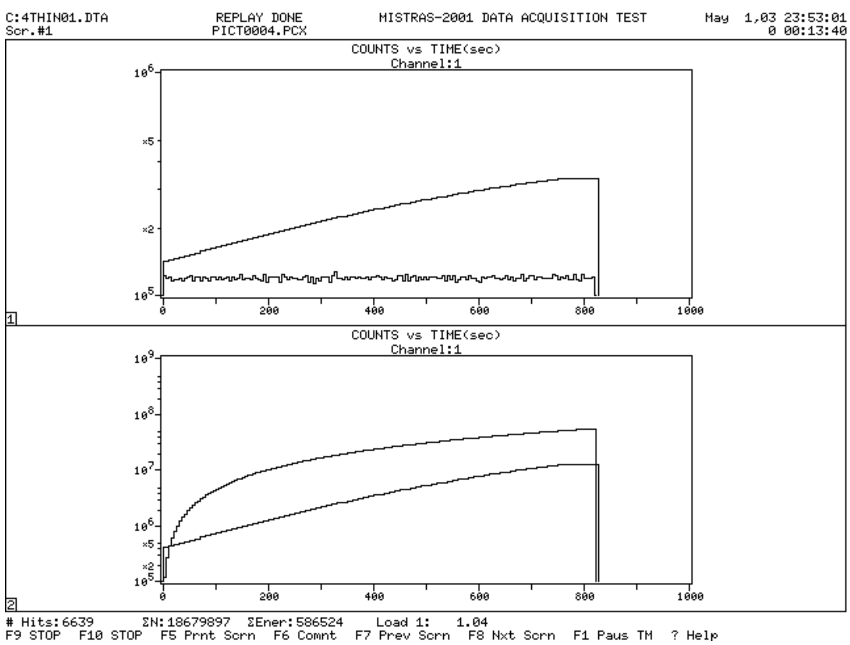


Figure 21a. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during the initial loading. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

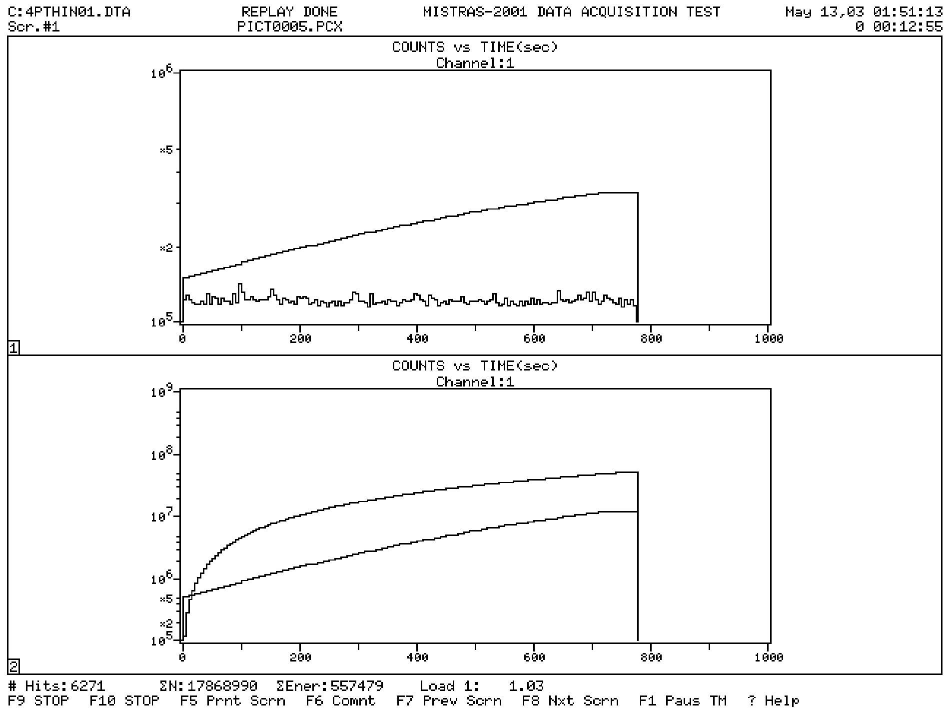


Figure 21b. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during reloading following Zn plating. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

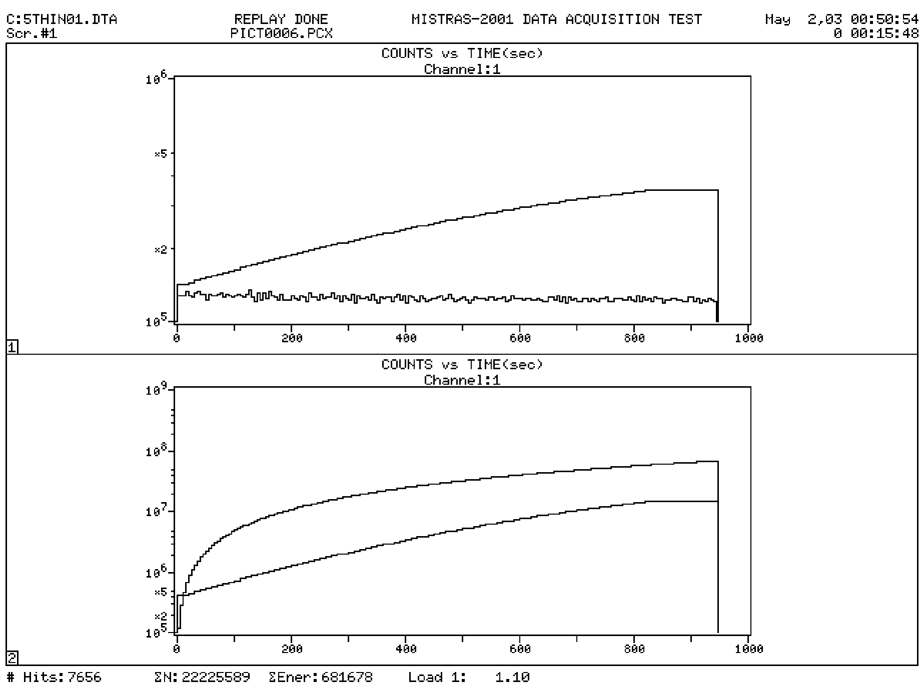


Figure 22a. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during the initial loading. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

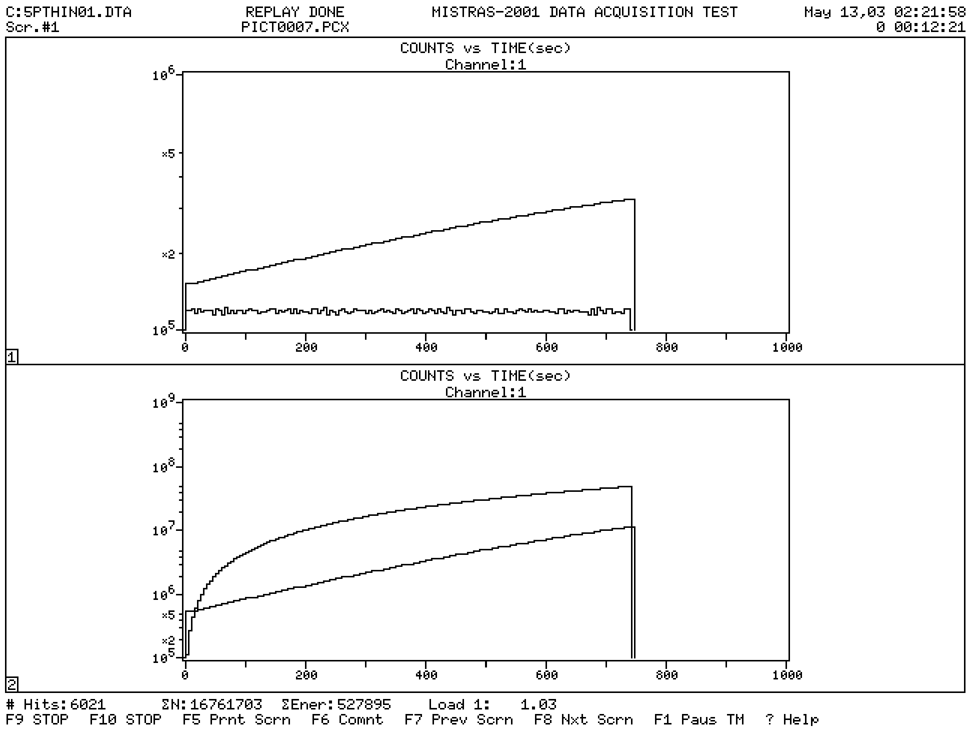


Figure 22b. Plots showing 1) the AE counts versus time and 2) the summation of AE counts versus time during the reloading following Zn plating. Superimposed on both plots is the load versus time, where full scale represents 2000 lb.

Figures 23 through 26 are some examples of individual AE that were collected during the initial and reloading of the three thin HPS70W specimens showing the similarity of these AE both before and after plating intended to induce hydrogen microcracking. The format of the images is such that the traditional Fast Fourier Transform (FFT) amplitude spectrum11 is shown at the top and the Wavelet Transform[12,13] image is shown at the bottom. The reader is reminded that the FFT displays frequency content present in the signal, while the wavelet analysis offers an indication of when the spectral components were present in time during the signal, in this case the AE record.

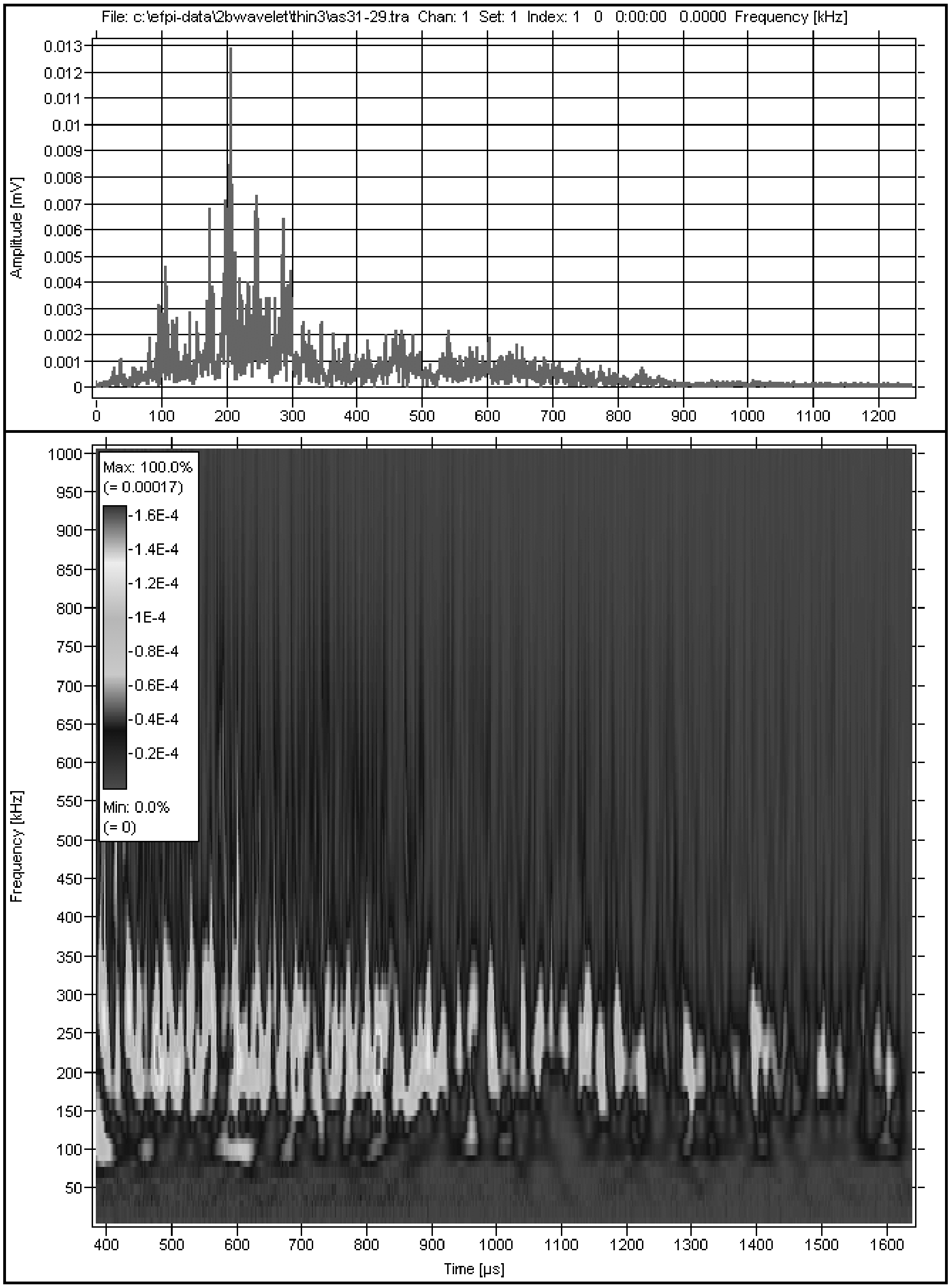


Figure 23. (top) Fast-Fourier Transform (FFT) amplitude versus frequency plot for an AE signal detected during the initial loading of a thin HPS70W specimen, (bottom) Wavelet Transform, frequency versus time.

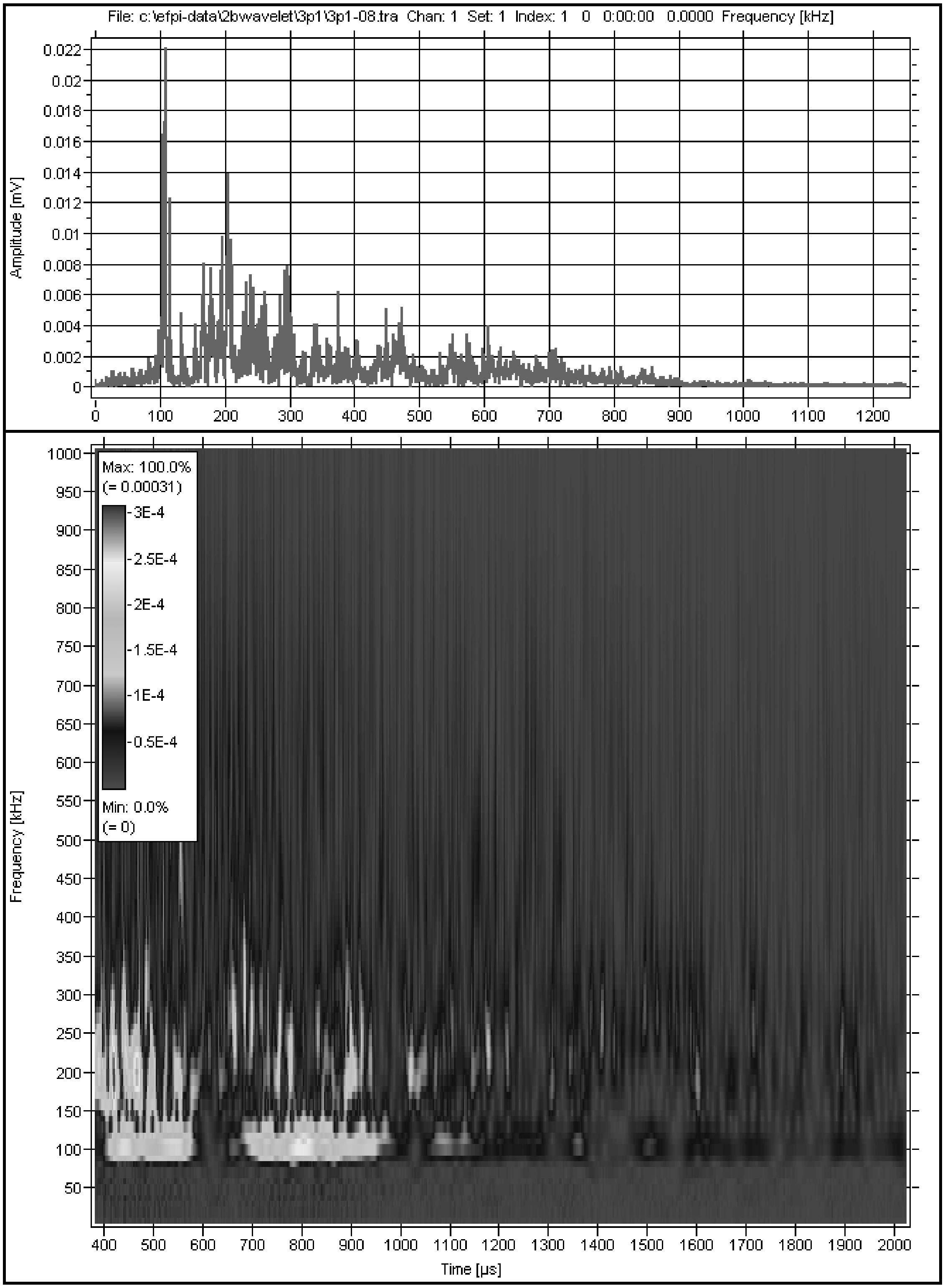


Figure 24. (top) Fast-Fourier Transform (FFT) amplitude versus frequency plot for an AE signal detected during the initial loading of a thin HPS70W specimen 3 after plating, (bottom) Wavelet Transform, frequency versus time.

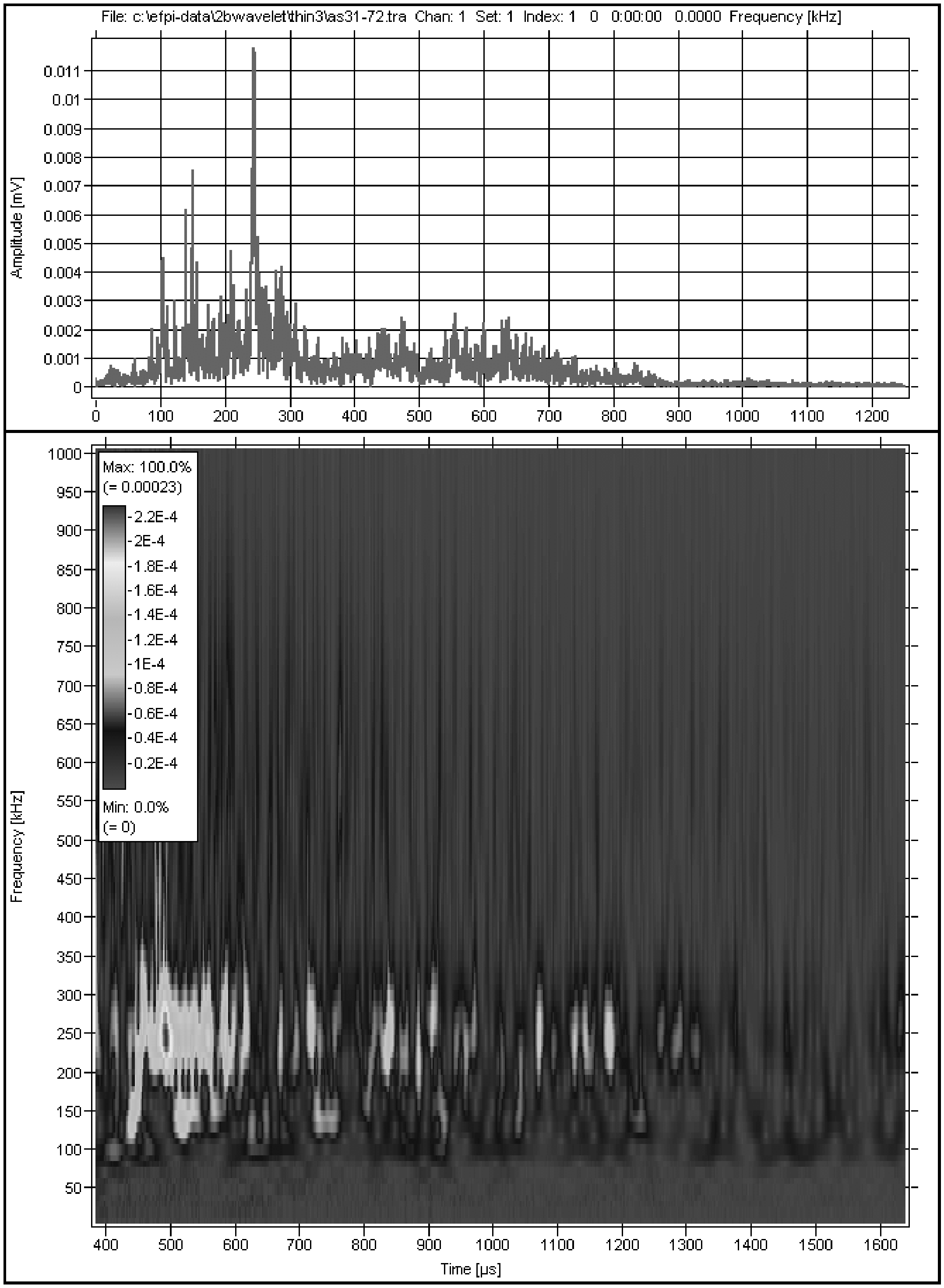


Figure 25. (top) Fast-Fourier Transform (FFT) amplitude versus frequency plot for an AE signal detected during the initial loading of a thin HPS70W specimen 3, (bottom) Wavelet Transform, frequency versus time.

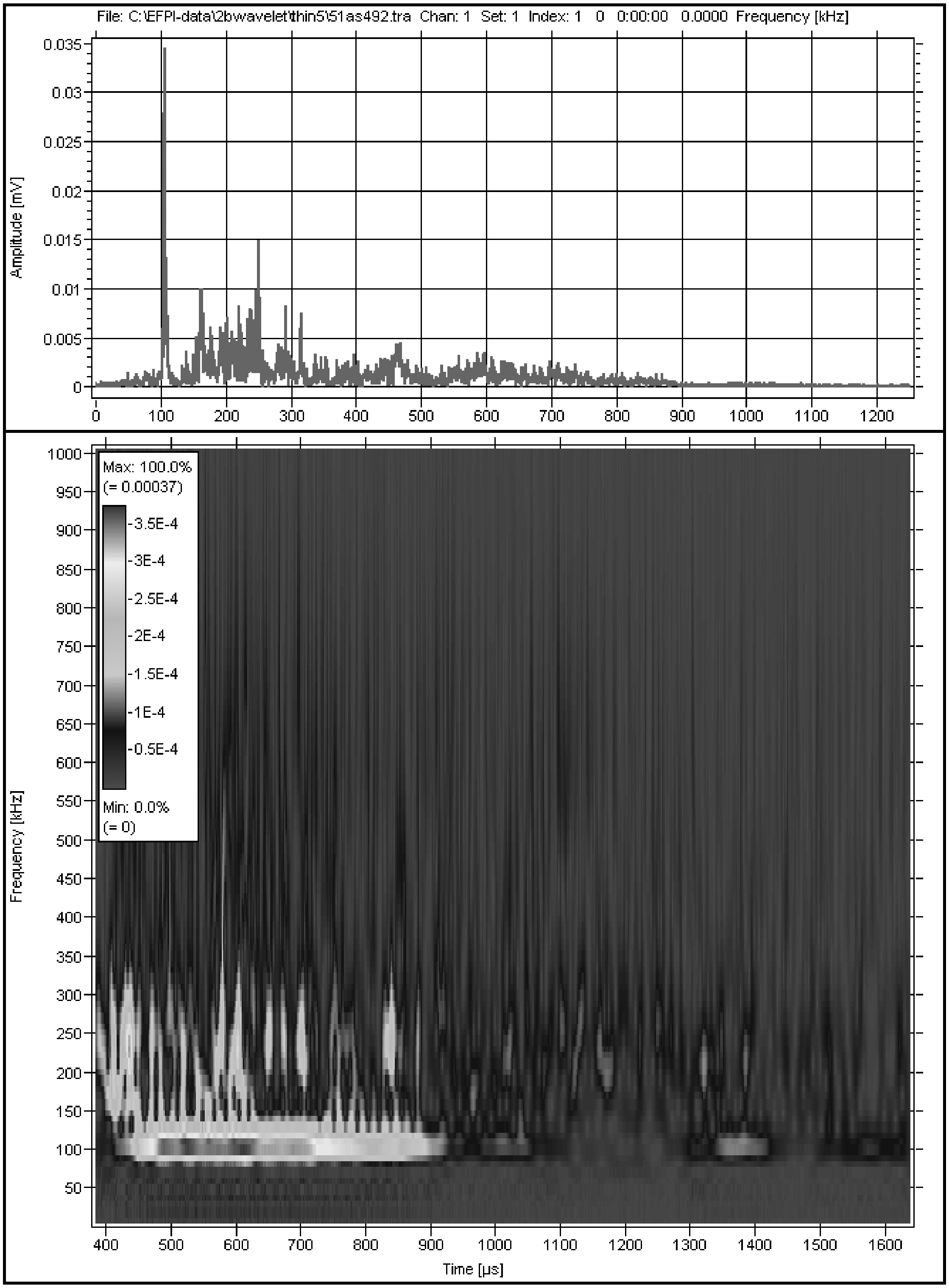


Figure 26. (top) Fast-Fourier Transform (FFT) amplitude versus frequency plot for an AE signal detected during the initial loading of a thin HPS70W specimen 5, (bottom) Wavelet Transform, frequency versus time

Extensive efforts were taken to produce microcracks in welded HPS70W specimens due to hydrogen embrittlement without obvious success. While it can be definitely stated that no macrocracking occurred, AE monitoring was used to determine the occurrence of microcracking. In that no significant AE was detected upon reloading of specimens plated with Zn in an effort to introduce hydrogen, it is speculated that microcracking did not occur.

After the review of the technical literature and conversations with welding experts, in particular welding engineers with Lincoln Electric, it was determined that hydrogen-induced microcracking can indeed occur in HPS70W when it is welded. Furthermore, other scientists have reported using AE to detect the occurrence of hydrogen-induced microcracking in carbon steels. [Note: The work in the literature actually describes charging by means of cadmium electroplating, however, because of the associated health risk with such a process the procedure utilized in this effort involved zinc plating. This plating performed by a local company, Electroplate Rite, Dublin, Virginia, was done so based on considerable experience of the plant manager who was convinced that hydrogen embrittlement was highly likely to result from the procedure used. In fact, the process used by the company is so prone to producing hydrogen embrittled steel that the plating process is followed by a step in which the parts are baked for 2 hours at 400^{o}F to drive off the hydrogen introduced during the plating process.] However, it is also clear from the literature as well that hydrogen although essentially always present during welding only in certain instances results in hydrogen embrittlement. An appropriate combination of temperature and stress along with sufficiently high levels of hydrogen must be present for embrittlement to occur. Often, under seemingly identical conditions, embrittlement may not always occur.

Since hydrogen-induced microcracking was not observed to occur, determining whether AE monitoring could detect growth or interaction of microcrack faces during cyclic loading was not possible. Results of testing to support the principal objective and allow for distinguishing between AE from plastic zone formation and extension of macrocracks suggests that AE monitoring can detect subtle forms of damage development.

Hydrogen introduced by plating tends to be present in higher concentrations near the surface and as such is more likely to rapidly diffuse out of the steel, than hydrogen introduced during a full penetration, multi-pass weld. Conversations with Dr. David Prine at Northwestern University regarding proprietary testing done while he was employed by GARD, the research division of GATX, under contract to the Army indicate that they had limited success detecting hydrogen-induced cracking with AE monitoring during welding. One might imagine the difficulty in detecting such AE from one part of a bridge girder that has begun to cool down while another area is still undergoing the welding process, while such detection from small welded plates would present a much quieter environment.

CONCLUSIONS

- AE can detect subtle forms of damage development associated with plastic zone formation and crack extension. However, HPS70W, a steel formulated with a microstructure that produces improved welding performance and strength has resulted in a material that emits significantly less AE than traditional bridge steels.

- It was not possible to induce hydrogen microcracking in HPS70W base metal, weld heat effect zone, or weld metal by acid precleaning and zinc plating that resulted in significant AE. This procedure had been found to induce hydrogen embrittlement in other carbon steel parts, by the electroplating company.

- Hydrogen-induced microcracking of weld metal may occur for welded HPS70W according to Lincoln Electric engineers; the likelihood is no greater than for other bridge steels at this point in time.

RECOMMENDATIONS

1. If the costs associated with detecting and repairing delayed, or cold, cracking due to hydrogen embrittlement are considered too high even due to infrequent occurrence, every precaution possible should be taken. This would include preheating the steel, either baking the consumables or using specially packaged consumables, and post heating to drive off excess hydrogen absorbed during welding. This recommendation is consistent with a specification-based procurement policy.

2. To reduce the added cost associated with the precautions for each and every bridge project, an effort should be undertaken to develop a nondestructive weld inspection procedure that can reliably detect the presence of hydrogen-induced microcracking. This recommendation supports a performance-based philosophy.

COSTS AND BENEFITS ASSESSMENT

The cost of enhancing an AE system to handle the high-speed data acquisition required for this application is on the order of $25,000. This is a one-time cost. This system could be incorporated into VDOT’s weld inspection requirements in Section 407.04(l) of the *Road and Bridge Specifications*. The weld inspection requirements are in place for quality assurance of a fabricated structural element before it is accepted and erected to form a bridge structure. Flaws resulting from welds will ultimately result in the formation of cracks in steel structures.

Once a structure is in place, such cracks are typically not discovered until a sizeable fracture has occurred (*sizeable* meaning detectable by the human eye). The initial cost of the enhanced AE equipment can be contrasted with the cost to VDOT of repairing a crack in a steel structure using current procedures. The cost to repair a crack in a structure in service may be on the order of tens of thousands of dollars, depending upon many factors. Once a repair has been performed, periodic inspections must occur to determine if, in fact, the crack has been arrested. Experience has demonstrated that once a crack is detected in a steel element of a structure, the structure is prone to developing multiple crack sites. Repair and continued monitoring may drive the costs to be on the order of hundreds of thousands of dollars in steel structures.

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