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ACOUSTIC EMISSION WELD MONITORING OF NUCLEAR COMPONENTS

by

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ACOUSTIC EMISSION WELD MONITORING OF NUCLEAR COMPONENTS

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D. M. Romrell

ABSTRACT

Acoustic emission is defined as the elastic waves produced in solid materials by an energy release as the material is deformed or fractured. These elastic waves travel through the solid material at the speed of sound and can be detected at the surface with sensitive acoustic emission sensors. This provides a basis for a technique of monitoring metal structures during welding processes to detect the formation of anomalies such as micro-cracks. On many structures, acoustic emission monitoring can provide both quantitative and flaw location data.

Acoustic emission monitoring augments other nondestructive testing methods and is sometimes applicable when other tests cannot be applied. This is, in part, due to the high sensitivity of acoustic emission monitoring. Acoustic emission monitoring is only sensitive to active flaw-growth, however, and will not detect a flaw in equilibrium.

This paper describes the application of acoustic emission monitoring to nuclear reactor fuel pin end closure welds and other weldments of the reactor piping.

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ACOUSTIC EMISSION WELD MONITORING OF NUCLEAR COMPONENTSINTRODUCTION

Acoustic emission (A.E.) monitoring techniques are utilized to detect the elastic pressure waves that are produced as energy is released in solid materials during deforming or fracturing processes. The detected pressure waves are converted to electronic signals that are processed to provide an indication of the rate and extent of material degradation.

A. E. monitoring has proven to be a useful nondestructive testing tool for detecting crack growth in many types of solid materials such as ceramics⁽¹⁾, metals^(2,3,4,5), and composites⁽⁶⁾ and is sensitive to micro-crack formation that cannot be detected by other NDT methods.

By utilizing sophisticated logic circuitry and a small digital computer, additional processing of the output data can be performed to greatly enhance A. E. methodologies. This includes deriving the emission source location data on a statistical basis and providing a real-time video display of the emission source locations. The source location spectrum is of particular interest when monitoring welds that are being fabricated in larger structures such as large diameter piping or plate sections. In these applications, after suspected crack areas are located, other NDT methods can be utilized and the necessary repairs can be made. Because some emissions occur during most welding processes, that are probably due to the welding arc or stress releases during metal solidification and cooling process, the emission source location spectrum is valuable for indicating areas of unusually high emission activity. A. E. monitoring can be sensitive to micro-crack formation at levels that cannot be detected by other NDT methods. This often makes data verification difficult. Also, the sensitivity level adjustment can be very critical during weld monitoring and should be determined for each welding process.

This report describes the application of acoustic emission monitoring to a few nuclear components including: the Fast Flux Test Facility (FFTF) reactor fuel pin end closure welds, the FFTF closed loop seal welds, and butt welds for 8" piping. A comparison is made between the recorded emission data and the destructive metallurgical examinations of some of these welds.

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A. E. Monitoring of Fuel Pin End Closure Welds

Because the weld area on the fuel pin end closure is small, the computer display of the emission source location spectrum is not applicable for this weld process. Thus, only the emission rate is used to provide an indication of the weld integrity.

THE MONITORING SYSTEM

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The monitoring system, preamplifier, and sensor used during the fuel pin end closure weld tests are illustrated in Fig. 1. The A. E. sensor is lead zirconate titanate (PZT-5) and has a resonant frequency response to acoustic emissions centered at 700 KH_2 . A spring loaded sensor holder (inset to Fig. 1) facilitates rapid changing of the fuel pin tubing and provides a reproducible method of coupling the sensor to the tubing. A thin silicone rubber layer, that is bonded to the sensor face, couples the elastic pressure waves from the tubing to the sensor as it is held against the tube under spring load. In this welding process, the tube is held stationary by the welding chuck while the welder tip rotates around the fuel pin assembly. The preamplifier utilizes a tuned feedback circuit to increase the signal to noise ratio and it is housed in a heavy aluminum case to ensure adequate shielding from stray electrical signals. The monitoring system conditions the electronic signals from the preamplifier and provides an analog output signal that is proportional to the incoming signal energy and repetition rate. The output from the monitoring system is recorded on a strip chart recorder and an oscilloscope provides a video display of the emission signals.

CALIBRATION PROCEDURES

Considerable emphasis in this work has been devoted to developing monitoring procedures that could be reproduced from weld to weld. This included the development of a calibration tube for use in calibrating the monitoring system prior to monitoring each test-weld series. The calibration tube was fabricated by bonding a piezoelectric element to the inside end of a 12" section of fuel pin tubing (Fig. 2). To calibrate the

770572 0931

monitoring system, the calibration tube is inserted into the welding chuck and clamped in an indexed, rotational and horizontal position, with the piezoelectric element connected to a pulse generator, pressure waves are transmitted into the calibration tube to simulate emission signals that are detected by the A. E. sensor which is positioned against the calibration tube. This provides a known input signal that facilitates calibrating the monitoring system by alternately adjusting the threshold level and the amplifier gain, thus providing a zero and span calibration for the output of the monitoring system. This provided a method of obtaining a calibration that is reproducible to within $\pm 2\%$ of the full scale range used for monitoring the end-closure welds.

Initially, more than 100 welds were monitored to characterize the welding process and to establish the proper A. E. monitoring range. Many low level emissions occur during the normal welding process that could possibly have been created by energy releases during the metal melting and solidifying processes or by the welding arc. While using the monitoring range and threshold adjustments selected for this welding process, these low level emissions contributed very little to the recorded emission data. The emissions from crack formation are, in general, significantly larger and are recorded.

Reference Weld

As a method of determining the functional behavior of the welding system and to establish that externally induced mechanical or electrical noise is not being detected by the A. E. monitor, a reference weld is made prior to starting each weld series and periodically thereafter. The reference weld is conducted by inserting a solid 316 stainless steel rod into the welding chuck and monitoring for acoustic emissions as a bead is welded around the rod. Under these conditions, all of the normal welding processes are performed without joining two parts together and the high thermal stresses at the root of the weld are minimized. This produces consistent welds with very low emission rates. A comparison between the emission rates from a reference weld and those from a weld in which micro-cracks were found is illustrated in Fig. 3. As the welding

arc is initiated, a full scale reading is briefly recorded on the A. E. chart recorder as a result of the high frequency burst that initiates the welding arc. The recorder, however, returns to normal operation within 2 sec., and since the total weld time is approximately 24 sec., this does not detract from the validity of the subsequent weld monitoring data. The full scale reading at the start of each weld is useful as a weld start-time record.

Fuel Pin Assembly and Metallographic Examination Procedures

The fuel pin assembly, illustrated in Fig. 4, includes a 316 stainless steel tube, that is .230" in diameter and 93.80" long, and end caps that slip into the ends of the tubing and are welded in place using a tungsten-inert-gas fillet type weld. A vertical cross-section of the fuel pin end closure weld area is illustrated in Fig. 5. The metallographic examinations of the welds discussed in this report were made by sectioning the tubing just below the weld root area and then polishing through the weld root area in planes perpendicular to the tube axis using .001" increments. Photomicrographs were made of all the anomalies that were found. Figure 6 illustrates the end of a tube that has been sectioned just below the weld root area and an expanded view of micro-crack formation at the weld-to-end cap interface.

It is believed that the weld root area is most susceptible to crack formation due to the localized thermal stress concentrations that are present during the weld cooling period. Thus, only this area was examined in detail and micro-cracks in other parts of the weld would not have been found. The expense and time requirements for a more detailed metallographic examination on this scale were not justified.

Acoustic Emission and Metallurgical Examination of Welds

To date, several hundred bottom end closure welds have been monitored. A few of these have been selected for detailed metallurgical examination to study the weld structure and to identify anomalies that would release emissions during the welding and cooling processes.

Of the welds that have been examined to date, there appears to be a relatively good correlation between the total emissions recorded and the micro-cracks found. Figure 7 illustrates the high emission rates recorded from weld sample R3-9 and a few of the many anomalies and micro-cracks that were found. The full scale indication at the beginning of every weld is caused by the high frequency burst that is used to initiate the welding arc, as previously described, and should not be included as part of the emission data. Because these photomicrographs were taken in the weld root area, the dark, sometimes non-continuous, line is the spacing between the end cap and the tubing. The points of interest are the irregular micro-crack lines and the curved micro-fissures.

Similarly, many anomalies and micro-cracks were found in weld sample R3-002 (Fig. 8) which again produced high emission rates. Only one area of sample weld No. 11 (Fig. 9) showed possibilities of being a source of emissions and the corresponding emission rates were much lower with no full scale indications after the weld initiation time. Figure 10 illustrates the low emission rates from sample weld R3-8. No micro-cracks could be identified with the few anomalies that were found in this sample. Weld R3-8 was, however, sectioned too close to the root of the weld and the data from this weld may not be complete.

A graph illustrating the correlation of the total emissions recorded and the corresponding micro-crack areas would be most interesting but cannot be made from the available data due to 1) the complexities of the micro-crack formation, 2) the limited views of the crack surfaces in the photomicrographs, and 3) the fact that several off scale emission indications were recorded that cannot be evaluated on an absolute basis.

A. E. MONITORING OF THE FFTF CLOSED LOOP SEAL WELDS

The purpose of this study was to investigate the feasibility of using A. E. methodologies for monitoring the FFTF closed loop seal welds. Other nondestructive testing methods could not be applied to this welding

770572 0934

process which would be conducted remotely below the reactor access floor due to material configurations and because the weld would not be readily accessible. Weld tests were conducted by welding a metal seal, that was fabricated of 308 SS at the weld area, to the inside of a 7.85" OD, 316 SS, spool piece. In this welding process, two welding tips, that are held stationary while the weld test specimen rotates approximately 210°, are used to minimize thermal distortions.

Monitoring System

The A. E. monitoring system used for this study (Fig. 11) consists of a two-channel monitor with the output addressed to a digital computer that is programmed to provide a video display of the emission source location spectrum. Additional outputs of the monitoring system, emission rate and emission summation, are recorded on a two-pen strip chart recorder. The inset to Fig. 11 illustrates two 500 KHz A. E. sensors mounted on an outer seal weld spool piece that is utilized as a weld-test specimen. Because only two sensors were used with this weld monitoring system, peaks in the source location spectrum represent two possible locations; i.e., the two corresponding locations on each side of the pipe. An expanded A. E. monitoring system has been developed for monitoring multidimensional test articles. This system utilizes 3 sensors for monitoring pipe welds and thus eliminates the 2 location ambiguity of this system.

SEAL WELD TEST PROCEDURE

Preliminary tests were conducted by monitoring a spool piece test specimen as reference welds, as described previously, were welded in the solid base metal above the seal weld joint. The reference weld was useful for assuring that the A. E. monitor and the welding system were functioning properly and provided a basis for comparing subsequent weld monitoring data. Figure 12 illustrates the emission source location spectrum from a standard reference weld and from a reference weld that was spiked with tungsten to produce a crack in the weld. The source location spectrum identifies the approximate crack location and the peak amplitude is relative to the extent of crack formation. The vertical lines in Fig. 12 are computer controlled markers that identify the center of the spectrum and the boundaries to be viewed on the video display.

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Several seal weld test specimens were monitored during the welding and cooling periods. For welds that had suspected crack areas, emissions were detected for more than 15 minutes after the weld was completed. Two outer seal weld specimens that were monitored were selected for destructive metallurgical examination. Standard welding procedures were followed while welding the first of these two test welds (Weld AE-1); but the second weld (Weld AE-2) was spiked with tungsten in two places, area 1 and area 2, to produce cracks. A surface crack was observed at area 1 and there was a corresponding peak in the emission source location spectrum. Surface cracks were not visible at area 2 and the emission source location spectrum was not significantly above the background level for this area. The source location spectrum for welds (both welds AE-1 and AE-2) had high background levels and contained peaks in the data that did not correspond to either areas 1 or 2 of weld AE-2. These welds were inspected by X-ray and ultrasonic methods, but because the outer spool piece wall is .655" thick and the weld only penetrates a small portion of this, X-rays did not detect any crack formation. In addition, ultrasonic inspection failed to locate any cracks.

DESTRUCTIVE METALLURGICAL MICROSCOPY

Several sections were removed from the two test weld specimens, described above, to be destructively examined. Figure 13 illustrates the schematic of a sectioned sample that has been removed from the weld specimen. Surface "A" of the sectioned samples was removed and examined in .005" increments through the weld root area with the increment increased to .020" through the remainder of the weld. Metallurgical microscopy verified the presence of a crack approximately .030" long in weld area 1 of weld AE-2 but the only anomaly found in weld area 2 was less than .002" long. Figure 14 illustrates the comparison between the emission source location spectrum and the cracks that were found in areas 1 and 2.

To determine what caused the high background and the data peaks in other areas, sectioned samples from additional areas were metallographically examined. In all these weld samples, many lamellar separations

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were found in the spool piece base metal which was fabricated from 316 SS rolled plate. The lamellar separations near the weld area would be stressed perpendicular to their length during the welding process and would probably be extended. Figure 15 illustrated the emission location spectrum from area 8 of weld specimen AE-1 and illustrates a few of the lamellar separations that were found in this area.

A. E. MONITORING OF PIPE BUTT WELD

In connection with the seal weld study described above, a few butt welds were conducted on 8" 304-L SS pipe spool pieces. These tests also included conducting a reference weld in the base metal to provide a system check and to provide a comparative basis for subsequent test data. During one of these tests, the dual welding torches were utilized to perform inside and outside welds simultaneously. Since this was not a full penetration weld, gas was entrapped during the first weld pass and as a second weld pass was conducted, a gas blow-out occurred. This produced emissions that continued for several minutes after the weld was completed and resulted in a significant peak in the source location spectrum. An additional peak in the spectrum for this weld indicated the location of a second suspected crack area. Metallurgical inspection of this weld was attempted, but in an effort to expose the center of the weld at a minimum cost, the weld root area was unintentionally destroyed and the subsequent examination did not produce meaningful results. Emission location spectra from the reference weld area, a normal weld area, the gas blowout area, and the suspected crack area for the 8" pipe weld tests are illustrated in Fig. 16.

SUMMARY AND CONCLUSIONS

A comparison of the acoustic emission (A. E.) data and the metallurgical microscopy from fuel pin end closure welds shows a degree of correlation that is encouraging and indicates that A. E. monitoring provides valuable nondestructive testing data. The weld samples that produced high emission rates were found to have several areas in which there were small micro-cracks. Weld samples that produced low emission rates had few or no micro-cracks. No macro-cracks were found in any of these welds.

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Although our efforts to establish A. E. Weld rejection criteria have been delayed in favor of additional metallographic examinations and weld development activities, it appears feasible to monitor all end closure welds on a production basis with a maximum weld time delay time of 1.5 minutes per tube. A. E. monitoring of the fuel pin end closure welds appears to provide a highly sensitive method of detecting micro-crack formation in these welds and provides test data unobtainable with other NDT methods.

Weld monitoring studies were also conducted on the FFTF closed loop seal welds and butt welds on 8" SS pipe spool pieces. A computer controlled monitoring system was utilized for these tests that provided a video display of the emission source location spectrum. For the closed loop seal welds, a comparison was made between the emission location spectrum and the metallurgical microscopy performed on sectioned weld samples from two test specimens. This comparison indicated that peaks in the emission location spectrum were created by a crack in a tungsten spiked area of the weld and by lamellar separations in the base metal that were probably extended during the welding process. For most of the welds where crack growth was suspected, emissions were detected for more than 15 minutes after the weld was completed. Although the tests conducted for A. E. monitoring of the FFTF closed loop seal welds and the 8" pipe welds were limited, the test data shows a good potential for utilizing the emission location spectrum for many weld monitoring applications.

In general, A. E. monitoring methodologies are being utilized in an increasing number of applications as a real-time weld monitor. This is in part due to new sophisticated instrumentation and interfacing of monitoring systems to digital computers to provide additionally processed data.

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ACCOUSTIC EMISSION (AE) SYSTEM FOR WELD MONITORING SYSTEM

FIGURE 1

FIGURE 2

COMPARISON OF EMISSION RATE MONITORING OF WELDS

FIGURE 3

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FIGURE 4

SAMPLED WELDED JOINTS: SECTION

FIGURE 5

METALLOGRAPHIC EXAMINATION OF END CAP WELDS

FIGURE 6

EMISSION RATE AND PHOTOMICROGRAPHS FROM SAMPLE WELD P3.9

FIGURE 7

EMISSION RATE AND PHOTOMICROGRAPHS FROM SYNTHETIC WELDED REGION

FIGURE 8

EMISSION RATE AND PHOTO MICROGRAPHS
OF WELDED SAMPLES WELDED NO. 10

FIGURE 9

FIGURE 10

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ACQUISITION SYSTEM WITH
ACQUISITION SYSTEMS

EMISSION SOURCE LOCATION SPECTRUM FROM REFERENCE WELDS

FIGURE 12

CLOSED LOOP WELD SAMPLE CUTAWAY

FIGURE 13

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FIGURE 14

SOURCE LOCATION SPECTRUM FROM A SECTION OF CLOSED LOOP
WELD SPECIMEN AE-1

PHOTOMICROGRAPHS OF LAMELLAR SEPARATIONS FOUND IN THE BASE METAL OF THE OUTER SPOOL
PIECE IN AREA 8

FIGURE 15

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FIGURE 16