Phased Array EMATS for In-Process Inspection of Welds

- Final Report -

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Prepared for

Advanced Technology Institute (ATI)
and
Northrop Grumman Newport News

ATI Subcontract Number 2003-345

1.0 Summary

The National Shipbuilding Research Program (NSRP) sponsored a limited investigation into the use of Electromagnetic Acoustic Transducers (EMATs) for in-process weld inspection. Working with Northrop Grumman Newport News shipyard, an experimental Phased Array EMAT system has been assembled and successfully tested for inspecting submerged metal arc welds while welding.

Successful application of EMAT technology has been demonstrated for near real time inspection of submerged arc welds in shipbuilding applications. The prototype system has been demonstrated to be successful on mock-up samples with artificially implanted defects. The EMAT system appears to be especially good at detecting and gauging the through wall extent of lack of penetration defects in the vertical land. The results of this testing indicate that this technology could be used to provide real time control of depth of penetration in some applications. Further research and development efforts would need to focus on developing a more robust system for shipyard applications and improving the phased array technique to eliminate spurious signals from the weld reinforcement.

The welding community has long recognized that a convenient means of performing non-destructive evaluation of welds either while welding or immediately after welding, could result in significant improvements in productivity and reduction in material loss, particularly in welds of heavy sections. Traditionally, non-destructive evaluation of welds is carried out using either x-ray or conventional ultrasonic testing after a weld joint has been completed. Neither of these technologies lends itself to evaluating the integrity of the weld while welding or shortly after welding. The high temperatures generated by the welding process and inability to monitor a partially completed weld joint are the main impediment to in-process or near real time weld inspection.

Traditional film based x-ray is likewise also not applicable because of the high temperatures generated in the component and inherent hazard to the welder due to radiation from the x-ray source, thus requiring personnel to evacuate the work area when radiographic examination is being performed.

The attached report details the research and development of the near real time EMAT weld inspection system.

2.0 Background

The welding community has long recognized that a convenient means of performing non-destructive evaluation of welds either while welding or immediately after welding, could result in significant improvements in productivity and reduction in material loss, particularly in welds of heavy sections. Traditionally, non-destructive evaluation of welds is carried out using either x-ray or conventional ultrasonic testing long after welding has been completed. Neither of these technologies lends itself to evaluating the integrity of the weld while welding or shortly after welding. The high temperatures generated by the welding process and inability to monitor a partially completed weld joint are the main impediment to in-process or near real time weld inspection. Conventional ultrasonic testing requires a fluid coupling medium in order to obtain reliable transmission and reception of the ultrasound through the transducer/component interface. Surface temperatures after welding can greatly exceed the boiling point of water, thus preventing it from being used as the couplant. Traditional film based x-ray is likewise also not applicable because of the high temperatures generated in the component and hazard to the welder due to radiation from the x-ray source, thus requiring personnel to vacate the work area when radiographic examination is being performed.

The National Shipbuilding Research Program (NSRP) sponsored a limited investigation into the use of Electromagnetic Acoustic Transducers (EMATs) for in-process weld inspection. Working with Northrop Grumman Newport News shipyard, an experimental Phased Array EMAT system has been assembled and successfully tested for inspecting submerged metal arc welds while welding.

2.1 EMAT Technology

The usefulness of ultrasonic techniques for inspecting welds is well established. Electromagnetic Acoustic Transducers (EMATs) are a form of ultrasonic transducers that offer several advantages over conventional piezoelectric transducers - primarily operation without a fluid couplant. This technique utilizes electromagnetic acoustic interaction for elastic wave generation. Therefore, no mechanical (fluid) coupling to the component is needed. The metal surface acts as its own transducer. This interaction is reversible; the EMAT works as a receiver. If an elastic wave strikes the surface of the conductor in the presence of a magnetic field, induced voltages are generated in the EMAT coil.

Figure 1 (Appendix A) depicts the fundamentals of ultrasound generation using EMATs for this project. An electromagnet is used to setup a quasi-static magnetic field in the surface of ferritic steel. A wire carrying a Radio Frequency (RF) current pulse, adjacent to the steel, sets up a dynamic magnetic field in the surface of the steel. The combination of the quasi-static and dynamic magnetic fields produces stresses in the surface of the steel via magnetostriction. These dynamic surface stresses launch ultrasonic waves. Typically, the wire coil, magnet, and electronics are tailored to produce an ultrasonic beam with specified characteristics.

EMATs can produce a variety of wave modes including surface waves, longitudinal waves, and horizontally polarized shear waves. The absence of a couplant makes it possible to design transducers that operate at elevated temperatures and allows rapid scanning. In addition, the operating characteristics of EMATs can easily be precisely reproduced from one unit to another. EMATs are conducive to automation, thus reducing issues with operator variability common to conventional NDE techniques.

One challenge to proper EMAT design is that the insertion loss of EMATs can be as much as 50 dB or more when compared to piezoelectric sensors. This makes instrumentation design crucial. EMAT pulsers are low impedance devices and EMAT receivers are specially designed units that exhibit low noise input when operated with low impedance loads. It therefore becomes important to choose applications where EMATs offer distinct advantages over piezoelectric sensors.

One of the most promising advantages for using EMATs in weld inspection applications is the ability to generate shear horizontal (SH) waves in a manner practical for high speed scanning. A transient line force in the surface of a solid material, with the force directed parallel to the line, produces SH waves with uniform amplitude and constant phase for all angles in a plane normal to the line. Figure 2 illustrates the shear displacement direction for SH and SV waves. SH waves reflect from surfaces parallel to the shear polarization with equal amplitude and without mode conversion for all angles of incidence. This is in contrast to SV and longitudinal waves which have complicated radiation patterns as a function of beam angle and can mode convert on reflection.

The use of SH waves results in several advantages for inspecting welds. Any beam angle can be used to inspect the weld from 0° to 90° (note: angles given are with respect to the through-wall direction perpendicular to the surface). Corner-type reflectors reflect SH wave beams with equal amplitude for all angles of incidence whereas SV wave beams employed with conventional UT can experience deep nulls in the reflectivity at incidence angles of around 30° and 60° due to mode conversion (Figure 3). A surface skimming (90°) SH wave beam can be used to interrogate the weld for incomplete fusion at the cap or crown of the weld that is not sensitive to the excess weldment or reinforcement in the weld cap. This is a result of SH waves matching the boundary conditions for both surface skimming and bulk wave propagation.

2.2 Phased Array Ultrasonic Inspection

An emerging ultrasonic inspection technology for industrial non-destructive evaluation (NDE) is the use of ultrasonic phased array sensors and systems. Phased array technology allows the generation of an ultrasonic beam with the ability to set the beam parameters such as angle, focal distance, and focal width through software. Figure 4 illustrates phased array operation. The transducer is comprised of an array of small individual elements. The elements are narrow so as to have enough beam-spread to launch ultrasonic waves over a wide range of angles. Each element is driven by an individual pulser. The time when each pulser is fired varies with element number such the waves traveling from each element arrive at the desired focal point at the same time. This effectively focuses the beam at that point. For reception each element is connected to an individual amplifier and signal delay device. The received signals from each element are delayed in time by an amount such that signals coming from the desired focal point coincide in time after the delays. The delayed signals are then summed together. This effectively focuses the receiver at the desired focal point.

The ability to dynamically change the properties of the probe provides many new possibilities for ultrasonic inspections. For example it is possible to quickly perform a linear scan of a region of a part without having to move the probe. It is also possible to vary the angle of the beam without physically changing the probe, providing multi-angle inspection of the part from a single point. Phased array technology allows the replacement of multiple probes and even mechanical scanning apparatus by a single phased array transducer.

2.3 Phased Array EMAT System

In order to address the need to characterize weld flaws in near real-time, a phased array SH wave EMAT system has been developed for the inspection of welds. This system combines the advantages of phased array technology with the advantages of EMATs to create a unique weld inspection tool. The system is capable of changing beam characteristics at rates up to 20,000 times per second, using up to 1,024 different configurations. For the inspection of magnetic materials such as carbon steel, the EMAT head consists of a pulsed magnet and flexible printed circuit EMAT coil driven by radio frequency (RF) currents. The system operates at an ultrasonic frequency of 2.25 MHz allowing high-resolution time of flight measurements.

Beam angle, focal point, and focal width in the vertical plane (perpendicular to the surface) are determined using well-known phased array principles. The focal width is determined by well-known relationships between aperture, distance to the focal point, and ultrasonic wavelength. Using phased array focusing, a focal spot of approximately 2 mm has been obtained, allowing through wall sizing of planar defects such as incomplete sidewall fusion in welds.

Welded plates and tubes are first prepared by cutting the surfaces to be joined together in specific patterns. For example, for automated welding, thick plate ends are typically cut with a bevel at the top and bottom of the plate for part of the thickness of the plate. A vertical land connects the top and bottom bevel (Figure 5). Obtaining complete fusion between the weld material and the component surfaces is of primary concern. By electronically scanning the focused beam along this fusion line, incomplete fusion areas can be detected and sized. In operation the EMAT probe head can be scanned next to the weld while monitoring the probe position along the length of the weld using an encoder. At predetermined distance increments, the phased array system is triggered and executes a series of ultrasonic interrogations of the weld, using configurations stored in the phased array instrument.

The flexibility of the phased array system coupled with SH wave generation allows a wide range of inspections with different beam angles, focal points, and focal widths to be performed. A phased array scan plan might include a focused sweep of the sidewall fusion line, inspections of the weld volume, interrogation of the root of the weld for incomplete penetration, and inspection of the cap of the weld for "undercut" or incomplete fusion at the upper surface.

A three-dimensional software simulator has been developed which allows the ultrasonic behavior of the phased array EMAT to be modeled. Arbitrary time-dependent excitation of the EMAT elements can be modeled and "snapshots" of the simulated ultrasonic wave packets obtained. Modeling has indicated that the EMAT probe used in this project is capable of a focal width as narrow as 1.5 mm (0.06”). Figure 6 shows a simulated profile of a focused SH wave beam for the conditions shown in Figure 13. The -6 dB beamwidth (pulse echo sensitivity) taken from the simulation is approximately 2mm (0.08)”. The length of the focal zone is approximately 20 mm (0.8”) which is ample for inspecting the fusion region as well as the adjacent regions of the weld. In many applications such high resolution is not required and a larger focal spot size can be used which increases the depth of focus for a given wavelength. The focal spot size can be tailored to meet the inspection requirements during the design of the EMAT probe and in configuring the phased array instrument.

The EMAT probe utilizes a flexible EMAT coil with a compliant backing that allows it to conform to the surface of the component being inspected. These flexible coils are relatively inexpensive when produced in large quantities. A thin flexible wear surface covers the EMAT coil and is designed for quick replacement. The flexibility of the probe and phased array system allow it to be used in a wide range of inspection applications. The coil, wear surface, and other materials used in the construction of the probe are capable of operating at up to 500º F.

This probe is useful for testing on ferritic steels having good magnetostrictive properties. This includes most of the common grades of structural steel and magnetic stainless steels. For inspecting nonmagnetic metals, SH wave EMAT arrays using permanent magnets can be constructed. However, the permanent magnet arrays are not flexible and must be contoured to match the surface to be inspected[1]. Recent efforts at developing inspection techniques for nuclear piping welds in the electric power generation industry have employed phased array permanent magnet SH wave transducers operating in the frequency range of 1-2 MHz.

3.0 Test Configuration

In order to test a phased array EMAT system for in-process weld inspection, BWXS has built an EMAT probe and configured a phased array EMAT system for operation on thick steel panel welds. NGNN has supplied weld samples, portable weld equipment, and personnel to conduct welding while scanning with the EMAT system.

3.1 Test Weld Configuration

A 1" thick grade DH-36 steel plate weld joint was chosen for evaluating the phased array EMAT system. The configuration of the joint is shown in Figure 7. The weld prep consists of a 30° bevel at the top and bottom of the plate for part of the thickness of the plate. A 3/8" vertical land connects the top and bottom bevel. This joint is normally welded using an automated submerged arc welding process.

3.2 Calibration Sample

A small, 1" thick sample of DH-36 steel was supplied by NGNN to serve as a calibration sample. The nominal weld prep was machined in one end of the plate and a 3/64" diameter side drilled hole was drilled in one edge of the sample (Figure 8). The hole was centered approximately 1/8" above the lower surface of the plate. A 3/64" diameter side drilled hole is used as a reference for conventional ultrasonic testing of welds at NGNN.

3.3 Phased Array EMAT System Electronics

1 J. Landrum and D. MacDonald, "Application of EMAT Technology to Piping NDE", EPRI 7th Annual NDE Issues Meeting, Charleston, S.C., July 9, 1997.

The phased array EMAT system electronics is comprised of a commercially available 32 active channel phased array UT instrument, 32 high power EMAT pulsers, magnet pulser, testhead preamplifiers, testhead transducer matching electronics, EMAT test head, interconnecting cables, and computers. A photograph of the system electronics is shown in Figure 9. The EMAT coils were operated at 2.25 MHz, corresponding to normal practice for inspecting welds at NGNN. Two computers provide system control, data acquisition, and data display (Figure 10). One computer is used to control the phased array electronics and to display raw data from the phased array electronics. A second computer is equipped with a waveform digitizer card for digitizing the received signals from the phased array system. These signals were then processed and displayed using a custom developed software routine. Signal processing included signal averaging, digital filtering, and digital envelope detection. Received signals were displayed mapped to actual part coordinates with an overlay of the weld prep for ease of interpretation.

3.4 EMAT Test Head

The EMAT test head consists of a pulsed magnet, 32 preamplifiers, 32 transmitter matching networks, a 32 element EMAT coil, wheeled chassis, and air manifold for cooling. A top view of the test head can be seen in Figure 11 showing the preamplifiers, matching electronics, and cables. A bottom view of the test head in Figure 12 shows the wheeled chassis, pulsed magnet, air manifold, and 32 element EMAT coil. The air supply hose can be seen going off to the left of the probe head. The wheels support the pulsed magnet and maintain a nearly constant distance from the polepeices of the pulsed magnet to the surface of the steel. A high temperature plastic wear surface is used to cover the flexible EMAT coils. High temperature sponge rubber backs the flexible EMAT coils and wear surface causing them to conform to the surface of the steel with light pressure to minimize wear. An air manifold is used to blow air over the EMAT coil to provide cooling.

3.5 Ultrasonic Configuration

3.5.1 Upper and Lower Bevel Inspection

The 32 element EMAT coil is designed with an active aperture used to form the beam. This large aperture allows the beam to be focused to a narrow focal width, even for operation at 2.25 MHz. Grating lobes are not present for this relatively large pitch because each element is comprised of several sub elements of alternating polarity. The range of angles over which the beam can be directed is limited by this arrangement from approximately 40º to 90º. Figure 13 shows the configuration for focusing the beam to the center of the upper bevel. A 60º focused beam is reflected off of the lower surface of the plate and then to the upper bevel region. Figure 6 depicts a simulation of the transmitted beam for this configuration. The distances in Figure 13 are given relative to the center of the upper surface of the weld joint. The focal width shown, 0.10” (2.5 mm) is for -6 dB transmitter beam amplitude drop. When operating in pulse-echo mode focused for both transmission and reflection, the theoretical pulse echo response beam width is 0.073” (1.9 mm). This allows for estimating the through wall height of weld defects by stepping the beam along the bevel fusion line and recording the ultrasonic response.

The lower bevel is inspected using a 60º focused beam in pulse-echo mode similar to the inspection of the upper bevel. The beam for the lower bevel inspection is sent from the transducer, bounces off the lower surface, then off of the upper surface, and then to the lower bevel. The reflected signal follows the same path but in reverse. Similar characteristics exist for inspecting the lower bevel as do for inspecting the upper bevel.

3.5.2 Vertical Land Inspection

In order to inspect the vertical land at the center of the weld the system is configured to sweep a focused 65º transmitter beam along the land and receive the reflections as shown in Figure 14. This is known as tandem operation. Effectively, a separate transmitter and receiver are formed. The parameters for this operation are given for two receiver configurations in Figure 14. The parameters for Receiver A are too close to the weld and in practice the reflected signal is allowed to bounce off of both the upper and lower surface to reach Receiver B. In operation a focused beam at 65º is bounced of off the lower surface and then to the land. Since the angle of the reflected beam from the land is equal to the angle of incidence, the reflected beam then strikes the upper surface, where it is reflected to lower surface, where it is again reflected to the receiver transducer.

This mode of operation provides for good detection and sizing of incomplete fusion defects in the land region. It makes full use of the unique advantages of the phased array EMAT system. The large apertures that can be formed allow ultrasonic beams with narrow focal widths to be used to sweep the land region, providing good through wall resolution. The use of SH waves allows an optimal beam angle of 65º to be used without mode converting, eliminating severe signal loss and extraneous signal generation as would be the case if conventional shear wave transducers were employed. By using phased array operation a separate transmitter and receiver can be formed with completely different beam characteristics even though the elements they use may overlap. It would not be possible to do this with conventional focused monolithic transducers because they cannot physically overlap. The use of phased array techniques also allow the land region to be scanned electronically, eliminating the need for mechanical raster scanning.

In many cases, current practice for ultrasonically inspecting vertical lands in welds employs a single transducer operating in pulse echo mode at angles of 45º to 70º. If there is incomplete fusion in the vertical land it appears as a planar reflector. Since the angle of reflection is equal to the angle of incidence, most of the reflected signal from these defects is reflected away from the transducer rather than back to it for these beam angles. This makes the detection and sizing of these defects with this method problematic.

3.5.3 Phased Array System Configuration

The phased array system was configured with three different virtual channels. The three channels were set up to inspect the upper bevel, lower bevel, and vertical land. Each channel fired 12 times at each position along the weld. For the two bevel channels the focused beam was electronically swept along the bevel fusion line in 1.14 mm (0.045") steps. The vertical land region was swept in 1.07 (0.042") mm increments. The use of 12 focal laws provided for over scanning of the inspected regions to allow for variations in probe positioning.

4.0 Testing

4.1 Elevated Temperature Testing

Testing was performed on mild carbon steel to establish the affect of temperature on signal amplitude and velocity. An EMAT probe was used to launch and receive 2 MHz surface-skimming SH waves in a block of 1018 steel. The probe utilized magnetostriction to generate and receive the SH waves. Heating elements were attached to the block and a temperature controller allowed the block to be heated to preset temperatures. The signal amplitude and time of arrival was measured as a function of temperature from room temperature to 500º F. This temperature range is thought to be typical for the surface temperature of welded steel components 25 mm (1") or more away from the weld itself.

Figure 15 shows received signal amplitude as a function of temperature. Figure 16 shows the calculated change in shear wave velocity vs. temperature. Figure

17 shows the measured change in time of flight vs. temperature and the calculated change in time of flight vs. temperature based on the calculated change in velocity as a function of temperature. There was a significant variation in signal amplitude observed as a function of temperature. However, useable signals were obtained at all temperatures. Interestingly, over the range of temperatures from 250º F to 500º F relatively small variations in signal amplitude were observed.

4.2 Initial Testing of the Phased Array EMAT System

Initial Testing of the completed phased array EMAT system was conducted on mild steel samples. Figure 18 shows the image generated by an angle sweep scan of a ¼" (6.4) mm diameter side drilled hole in a 1.5" (38mm) thick steel block. The beam was focused at the hole after bouncing off of the back wall and swept between 45 and 65 degrees in ½ degree steps. This test confirmed that the beam was being focused and steered as predicted.

In Figure 19 the response of the phased array system to the 3/64" (1.2 mm) diameter side drilled hole placed in the calibration sample is shown. The image is segmented into three parts. The upper segment shows the response for the upper bevel channel, the middle segment shows the response for the vertical land channel, and the lower segment shows the response for the lower bevel channel. Two images of the hole are apparent in Figure 19. The inset diagram shows the reason for this. The lower hole image is the correct reflection for this channel. The upper hole image is a result of the side drilled hole reflecting sound equally well for all angles of incidence and over scanning the bevel region. The upper hole image as shown in the inset diagram comes about when the beam reflects off of the upper surface and then the hole. The fact that the two images of the hole are nearly identical indicates a good depth of field has been achieved for the focused beam used here.

In Figure 20 the response obtained when looking at the end of the cal sample with the machined weld prep is shown. Large indications for the upper bevel, vertical land, and lower bevel are shown. Although the bevel regions were over-scanned, the over-scanned regions were not symmetrical about the bevels. This is a limitation of this prototype system.

4.3 Testing of NGNN Weld Sample 2003-20-1

A 31" long by 20" wide weld test sample was provided by NGNN containing defects induced while welding. Figure 21 shows the test sample and EMAT test head placed in a scanning bed used to scan the EMAT probe along the weld. The weld was scanned using the EMAT with encoder based firing for precise location information. Figure 22 shows the results of the scan of the land area of the weld. No indications were readily apparent in the bevel regions of the weld. Large indications were obtained in the vertical ligament regions of the weld. Some of the reflections in the ligament area were nearly the same amplitude as the reflections obtained from the machined weld prep in the cal sample, indicating incomplete fusion. This region was scanned using the electronic scan as described earlier for the vertical land region. The color C-scan image shows the indications obtained as the probe was mechanically scanned along the length of the weld. The scale at the bottom of the C-scan display is in inches and begins at the reference mark provided by NGNN. Incomplete fusion defects in the vertical land are indicated at 2”- 3” and 6.5” to 8.5” from the start, and a smaller indication from 11” to 12.5” from the start. In addition a smaller indication exists from the start out to 12.5” which may indicate a small defect at the center of the weld. Starting at about 14” from the start significant indications are visible at the lower edge of the display. These indications extend to about 24”. Likewise reflected signals also show up at the upper edge of the display from about 11” to about 21.5”.

Comparison of the EMAT results to handheld ultrasonic testing using a 2.25 MHz 60º pulse echo shear wave transducer produce agreement for some of the indications and disagreement in others. It is noteworthy that the EMAT system clearly indicates large incomplete fusion defects in the vertical land that were not clearly indicated by hand held testing. This is not unexpected since the two test methods employ very different approaches. In addition it is not known what defects are actually contained in the weld sample so it is difficult to draw conclusions from this data. The testing on this sample occurred early in the project and did not benefit from later enhancements to the EMAT system, primarily improvements in the data acquisition and display software. It was determined that the 10” wide plates used to form this weld sample resulted in interfering reflections off of the backside of the EMAT transducer for the bevel channels. In subsequent weld samples the plate widths were increased to 12” to eliminate the interfering signals.

The EMAT system operating in tandem mode has an advantage for detecting incomplete fusion defects in the vertical land. However for detecting other defects, especially volumetric type defects in this region, it may be advantageous to also scan this region with the focused 60º beam that is used to scan the upper bevel and lower bevel regions. This could be readily accomplished by adding additional focal law firings to the phased array configuration.

With handheld testing it is possible to skew the beam angle, improving the detection of defects that are misaligned with the length direction of the weld. At this time it is not possible to do this with the EMAT probe. Further investigation would be needed to determine what impact this may have on the inspection.

4.4 Testing of EMAT System Operation While Welding

Testing of the phased array EMAT system for inspecting welds while welding has been conducted at BWXS laboratories. NGNN supplied a portable submerged arc welder, power supply, and test plates for welding. Figure 23 shows the welder in operation on a weld test sample, with the EMAT probe attached to the weld head assembly. Figure 24 shows the EMAT probe attachment to the weld head. The center of the EMAT probe was set approximately 27" behind the weld head. This allowed time for the weld to solidify and cool somewhat prior to inspection. Figure 25 shows the weld, weld head, and EMAT probe while welding.

The welding test samples had been prepped and tack-welded at NGNN prior to shipping to BWXS. The joint was welded in two passes. The first pass welded the top half of the plates together. The sample was then flipped over and the weld was completed. Welding was performed using the mechanized submerged arc process. Welding consumables consisted of ESAB 40A 3/16" diameter electrode and Lincoln 860 flux. The first sided was welded using approximately 825 amps, 35 volts and 11 ipm travel speed and the second side using approximately 925 amps, 37 volts and 10 ipm travel speed. No second side root back gouging was performed. See Figure 44 for typical welding technique. Defects were introduced into the weld by changing a combination of conditions: decreasing amps by 500 and/or increasing travel speed; tilting or moving weld torch out of root alignment. Loose welding flux was removed in front of the EMAT probe by sweeping and the use of a compressed air jet.

The EMAT system was able to operate while welding with no apparent differences from operation without welding. Likewise, the weld pool did not appear to be affected by the magnetic currents of the EMAT. Precautions had been taken to prevent EMI from the welder from producing electrical noise on the EMAT signals. No increase in noise level was observed while welding. The EMAT probe was able to withstand the heat produced by welding with no apparent problems. Maximum temperatures at the EMAT coil were measured to be 200º to 300º F using an optical pyrometer. All ultrasonic waveforms were recorded while scanning. These waveforms were processed later for analysis and display.

4.4.1 Testing of Weld Sample 1

Figure 26 shows a display of a scan of weld test sample 1 prior to welding. The display consists of 3 C-scans, 3 A-scans, and 3 cross sectional views corresponding to the top bevel, vertical land, and lower bevel. The C-scans show color encoded peak amplitudes as a function of scan position along the weld (horizontal axis) and electronic sweep step (vertical axis). A curser can be moved through the C-scans and a cross sectional view of the received signals with an overlay of the weld prep is displayed (on the left hand side) corresponding to the horizontal position of the curser in the C-scan. An A-scan (waveform display) is displayed below the C-scans corresponding to the data at the intersection of the horizontal and vertical cursers. This provides a means of conveniently evaluating the received signals.

In Figure 26 strong indications show up in all three channels since the joint had not been welded at this time. The cross-sectional views show where the reflected signals for the weld bevel and vertical land show up for complete incomplete fusion. The system was calibrated so that the weld prep end of the cal sample creates an 80% of full screen height indication. Occasionally the data acquisition board will lose synchronization resulting in a vertical line that looks like noise in the display. This is a result of Windows latency issues and would not be a problem for a production testing system. Examination of the C-scan images clearly shows that the joint is unwelded down the entire length of the joint except where the upper and lower bevels are tack-welded together. Here the C-Scan images for the upper and lower bevels show regions where the signal amplitude drops down from red or black to light blue. The vertical land region does not show this drop in reflected signal indicating that it remains unwelded in these regions.

Weld test sample 1 was welded with the first pass. Unfortunately problems coordinating the data acquisition with the scanning prevented the recording of the signals while welding. Shortly after welding, the sample was scanned while the sample was still hot. The surface temperature where the EMAT probe scans was measured to be 200º to 300º F for this scan. The first pass should consume the upper bevel and part of the vertical land. The lower bevel should not be consumed for the first pass. Examination of the C-scans in the image shows that this is basically what has happened. The image for the lower bevel has remained basically unchanged from the scan prior to welding. The upper bevel C-scan shows almost no indications showing that the welding has consumed almost the entire upper bevel. The most interesting C-scan is for the vertical land region. This C-scan indicates that penetration on the vertical land varied from only partial penetration to almost complete penetration in some regions (indicated by the light blue areas near the bottom of the C-scan for the vertical land region).

Weld test sample 1 was then flipped over and the second weld pass was applied to the joint. The image from the EMAT Scan while welding is shown in Figure 28. For most of the weld complete penetration of the land and fusion of the bevels is indicated. At a little more than halfway down the weld the weld torch was moved off of the weld joint to create an incomplete fusion defect (Figure 30). The indication of incomplete fusion in the bevel and incomplete penetration of the land are clearly visible in the EMAT C-scans. Towards the end of the weld the welding current was reduced. Incomplete penetration of the vertical land region is indicated in the EMAT scan towards the end of the weld. An indication in the lower bevel C-scan occurs adjacent to the incomplete fusion indication for the upper bevel and incomplete penetration. This appears to be an anomaly, perhaps as a result of a complicated reflection path involving the incomplete fusion defects and the reinforcement. Likewise the earlier indication in the lower bevel towards the beginning of the scan occurs very late in time and is perhaps a reflection from reinforcement. Improved gating of the reflected signals in time would eliminate many of these spurious indications. Other smaller indications are also visible but have not been investigated.

Figure 29 shows a rescan of sample 1 side 2 after welding but while the surface of the plate was at 200º to 300º F in the region the EMAT scans over. The rescanned image closely resembles the image for scanning while welding with some notable exceptions. The incomplete penetration indication towards the end of the weld is much larger in amplitude for the scan while welding than for the rescan. This may be caused by forces being generated on the faces of the land by the cooling weldment, causing them to be pressed together for the rescan. This is a known condition which can allow some of the ultrasound to pass through this interface, reducing the amplitude of the reflected signal. This idea is supported by the fact that the incomplete penetration indication adjacent to the upper bevel incomplete fusion indication does not change amplitude as much in the rescan. Since the upper bevel is not welded here, compressive forces on the land interface do not formed as easily.

4.4.2 Testing of Weld Sample 2

Figure 31 shows the results of the EMAT scan while welding on weld test sample 2 side 1. This was the first weld pass. The C-scans for this run indicate areas of lack of fusion in the upper bevel in conjunction with indications of lack of penetration of the vertical land. The lower bevel appears to be unwelded except for the tack-welds. It is interesting to note the apparent ability to estimate the depth of penetration from the C-scan image of the vertical land.

Figure 32 is a rescan of the weld with the surface temperatures at approximately 200º - 300º F. Although the same basic features are apparent as in the scan taken while welding; there is a shift in the amplitude of some of the indications, especially for the upper bevel.

Figure 33 shows the results of the EMAT scan after test sample 2 was flipped over, prior to welding. This scan shows many indications in the lower bevel C-scan of unknown origin. It appears that when a large amount of the upper bevel and land are not welded, spurious reflections occur on the lower bevel channel.

Figure 34 shows the results of the EMAT scan while welding test sample 2, side 2 (second weld pass). Low welder current was used at the beginning the weld. Incomplete penetration and incomplete fusion of the upper bevel is indicated for the first part of the weld. The lower bevel continues be plagued by what appear to be spurious reflections. Subsequent testing indicated that these signals may be some sort of reflections involving the weld reinforcement.

Figure 35 shows the results of the EMAT rescan of the weld with a surface temperature of approximately 200º to 300º F in the region the EMAT probe scans over. This scan shows essentially the same features as the scan while welding. The lower bevel channel continues to be plagued with spurious reflections.

Figure 36 shows the results of the EMAT rescan of the weld after the sample has been allowed to completely cool to room temperature. The indications from this scan agree well with the indications from the previous 2 scans. It is interesting to note that there is a noticeable drop in the amplitude of the incomplete penetration indications at the beginning of the weld, after the weld has completely cooled. This again may be due to compressive forces generated on the faces of the land causing them to be pressed together, allowing ultrasound to pass through the interface and reducing the amplitude of the reflection. The lower bevel channel continued to be affected by spurious signals in this scan.

4.4.3 Comparison of Handheld UT Testing to EMAT Testing

NGNN personnel scanned the welded test samples using conventional UT 60 degree 2.25 MHz probes. The testing was conducted using the standard procedure for actual inspections at NGNN. All indications were recorded and the indications were marked on the weld test samples. Flaw maps were prepared for the two welded samples by NGNN personnel. Figures 37 and 38 show the flaw maps for welded samples 1 and 2 respectively. The map is not to scale so that the indications are more easily viewed. The table gives the location, length, depth, zone, and maximum signal amplitude for each of the individual indications. The amplitude reported is in number of divisions on the UT instrument display screen adjusted so that a 3/64s" diameter side drilled hole produces 8 divisions out of a maximum of 10. The upper box shows a top view of the location of the indications and the lower box shows a side view of the location of the indications.

Figure 39 shows a comparison of the EMAT response to the UT flaw map for sample 1. The C-scan image generated by the EMAT for the upper bevel, vertical land, and lower bevel are shown just above a to-scale flaw map for the UT indications. Figures 37 and 38 can be used to help interpret the to-scale flaw map. For this comparison the sensitivity of the EMAT system was set so that the reflection from the weld prep in the cal standard produced an indication that was approximately 80% of full scale. This level produces a red to black indication in the C-scan images. The color scale used to indicate signal amplitude is also shown in the lower left hand corner of the Figure. Since the weld prep generates large reflections, this setup required relatively low gain.

In Figure 40 the sensitivity of the EMAT system was set so that the reflection from the 3/64s side drilled hole in the cal block produced a indication that was approximately 80% of full scale. This level produces a red to black indication in the C-scan images. Since the 3/64s" diameter side drilled hole generates small reflections, this setup required relatively high gain. This setup emulates the sensitivity used for hand held UT testing at NGNN.

For this sample good correlation between the UT flaw map and EMAT response is evident. The EMAT images show strong indications corresponding to all the hand held UT indications in the flaw map. Incomplete penetration of the vertical land seems to be especially well detected with the EMAT system. The large indication at the beginning of the scan in the EMAT vertical land channel does not have a corresponding indication in the hand held UT flaw map. Analysis of the reflected signals with the EMAT system from this region indicates that this is an actual lack of penetration defect.

The hand held UT test used for these inspections utilized a 60º beam angle in pulse echo mode to try to detect these vertical land defects. Figure 41 illustrates the difference between the inspection of the land region with this hand held UT test and the EMAT test. Because of the 60º beam angle used in this hand held UT test, most of the reflection from lack of penetration of the land is directed away from the transducer rather than back to it. This method relies on small non-planar reflectors to scatter ultrasound back to the transducer in order for the lack of penetration to be detected. It is noteworthy that even large lack of penetration defects may not produce an indication with this hand held UT test since the presence of small reflectors in the defect is non-uniform. Hand held UT methods, utilizing two transducers, are used in certain applications to better examine the vertical land. This allows for greater discontinuity detectability in the land, but requires an additional scan.

For the EMAT test, a separate receiver is formed with the phased array sensor at the correct location to receive the direct reflection from lack of penetration of the land. The EMAT test also employs SH waves which do not mode convert on reflection, resulting in strong reflected signals from the lack of penetration defects.

The EMAT lower bevel channel had several spurious indications. Some on of these indications in the lower bevel channel appear to be caused by large reflectors in the vertical land. In fact, in Figure 40 for every large indication in the vertical land there is a large indication in the lower bevel channel. The gating in time used to process the signals was quite wide. Better gating would reduce the number of false indications. In Figure 40 there is a large indication in the lower bevel channel at about ¼ of the way through the scan. This was determined to be a spurious indication occurring late in time but within the gate. The source of this indication is not known at this time but may be a weld reinforcement related reflection. The gating and configuration of the lower bevel channel needs further investigation and improvement to eliminate the false indications.

Figure 42 shows a comparison of the EMAT response to the UT flaw map for sample 2. The C-scan image generated by the EMAT for the upper bevel, vertical land, and lower bevel are shown just above a scale flaw map for the UT indications. For this comparison the sensitivity of the EMAT system was set so that the reflection from the weld prep in the cal standard produced an indication that was approximately 80% of full scale. This level produces a red to black indication in the C-scan images. The color scale used to indicate signal amplitude is also shown in the lower left hand corner of the Figure. Since the weld prep generates large reflections, this setup required relatively low gain.

In Figure 43 the sensitivity of the EMAT system was set so that the reflection from the 3/64s side drilled hole in the cal block produced a indication that was approximately 80% of full scale. This level produces a red to black indication in the C-scan images. Since the 3/64s" diameter side drilled hole generates small reflections, this setup required relatively high gain. This setup emulates the sensitivity used for hand held UT testing at NGNN.

For this sample, good correlation between the UT flaw map and EMAT response is evident. The EMAT images show strong indications corresponding to all the hand held UT indications in the flaw map taken from the same side as the EMAT probe.

Again, incomplete penetration of the vertical land seems to be especially well detected with the EMAT system. There is a large indication at about ¾ of the way through the scan in the EMAT vertical land channel that does not have a corresponding indication in the hand held UT flaw map. Analysis of the reflected signals with the EMAT system from this region indicates that this is an actual lack of penetration defect.

The EMAT lower bevel channel had spurious indications throughout the scan. The source of these indications is not known for certain, but appears to be weld reinforcement related reflections. The gating and configuration of the lower bevel channel needs further investigation and improvement to eliminate the false indications. The gating in time used to process the signals was quite wide. The gating and configuration of the lower bevel channel needs further investigation and improvement to eliminate the false indications.

For weld test sample 2 (side 2) the locations of the indications from the handheld UT testing were re-examined by moving the EMAT probe along the track by hand. The larger amplitude indications from the handheld UT testing corresponded to EMAT indications of combined incomplete fusion of the bevel and incomplete penetration of the vertical land. The smaller UT indications corresponded to incomplete penetration indications using the EMAT probe. All handheld UT indications were also indicated by the EMAT testing.

5.0 Conclusions and Recommendations

The National Shipbuilding Research Program (NSRP) sponsored a limited investigation into the use of Electromagnetic Acoustic Transducers (EMATs) for in-process weld inspection. Working with Northrop Grumman Newport News shipyard, an experimental Phased Array EMAT system has been assembled and successfully tested for inspecting submerged metal arc welds while welding.

Successful application of EMAT technology has been demonstrated for near real time inspection of submerged arc welds in shipbuilding applications. The prototype system has been demonstrated to be successful on mock-up samples with artificially implanted defects. The EMAT system appears to be especially good at detecting and gauging the through wall extent of lack of penetration defects in the vertical land. Further research and development efforts would need to focus on developing a more robust system for shipyard applications and improving the phased array technique to eliminate spurious signals from the weld reinforcement.

The results of this investigation indicate that it may be possible to use this technology to provide real time feedback and control of depth of penetration in some applications. Adjacent to or just behind the welding torch, the surface of the steel at the location of the EMAT sensor has not had time to heat up, providing ideal operating conditions. As soon as the weldment has solidified it should be possible to detect and gauge the extent of penetration and provide feedback for controlling the welding apparatus.

6.0 Acknowledgements

This project was sponsored by the NSRP program with direction from the SP-7 welding committee. This project benefited from the hard work of a number of very talented individuals. From Northrop Grumman Newport News; Randy Gabbert (project manager), Steve Ashton, Chris Arnold, and Tony Harper. From BWXT Services; Steve Clark, Brad Cox, Tom Doyle, Ben Grimmet, Mark Gryder, Jimmy Hancock, Charles Overby, and Chris Rutherford.

Phased Array EMATS for In-Process Inspection of Welds

- Final Report - Appendix A – Photos and Diagrams

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Northrop Grumman Newport News

ATI Subcontract Number 2003-345

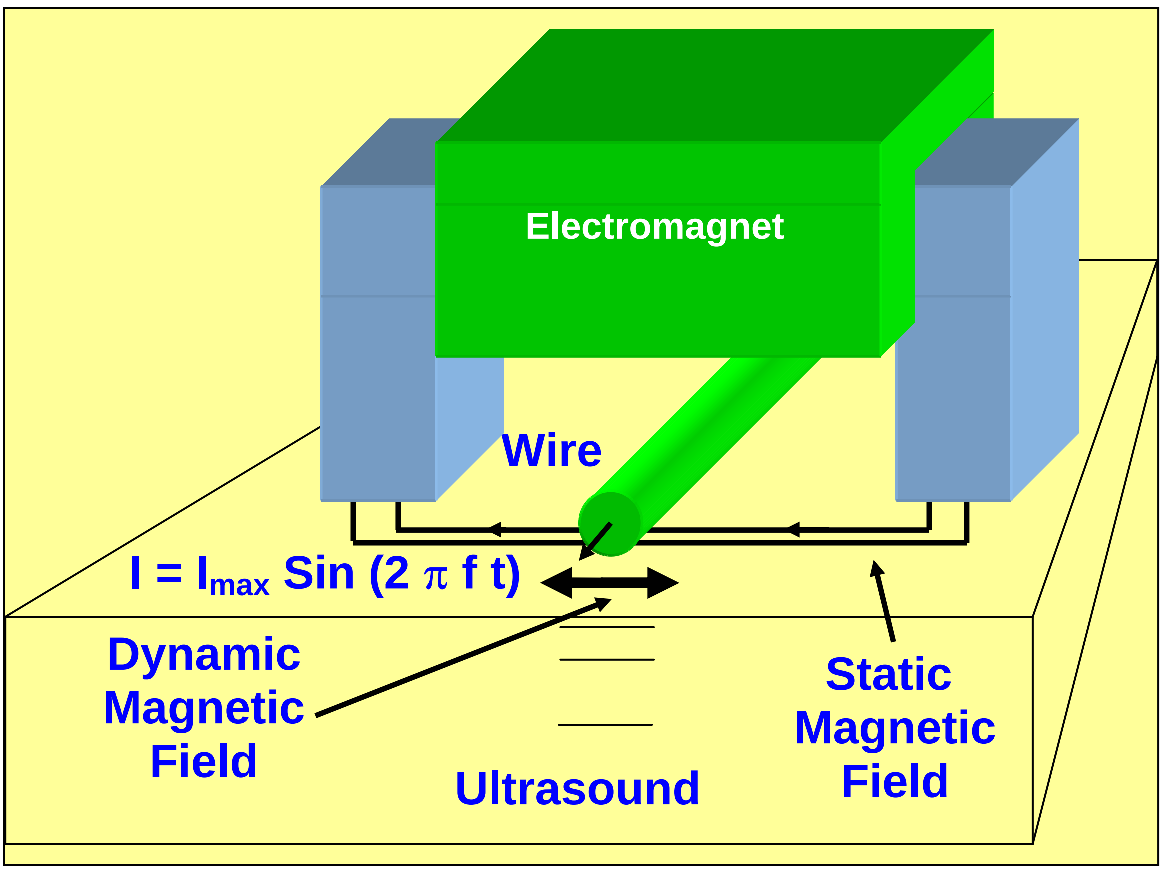


Figure 1 - Magnetostrictive Ultrasound Generation Using EMATS

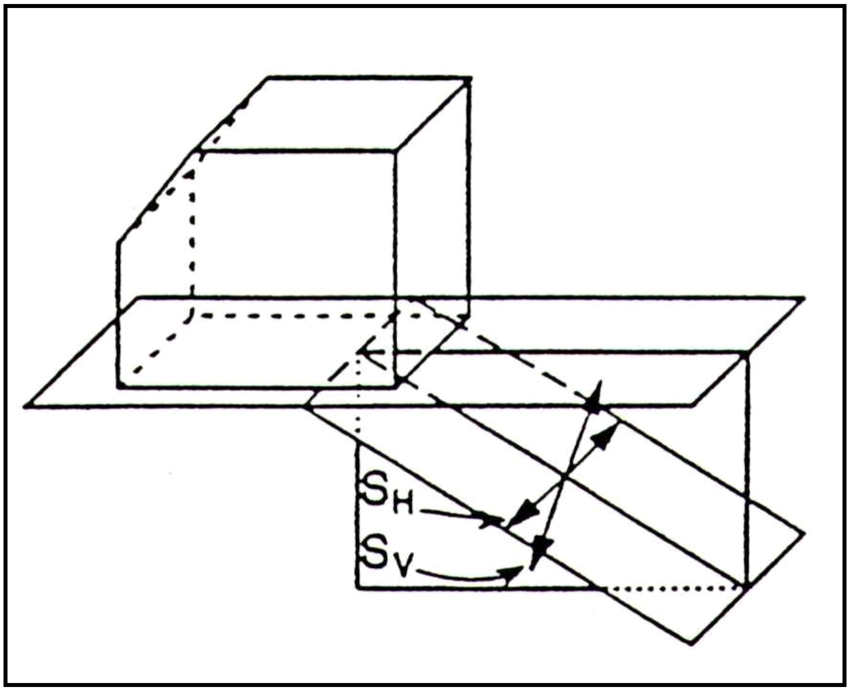


Figure 2 - Diagram Showing Shear Displacement Direction for SH and SV Waves.

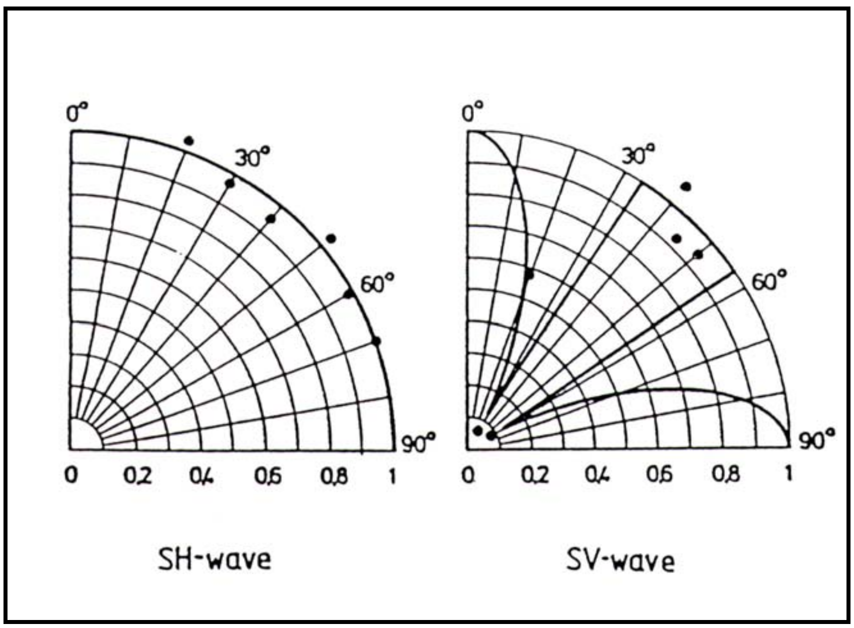


Figure 3 - Corner Reflection Amplitude vs. Beam Angle for SH and SV Waves.

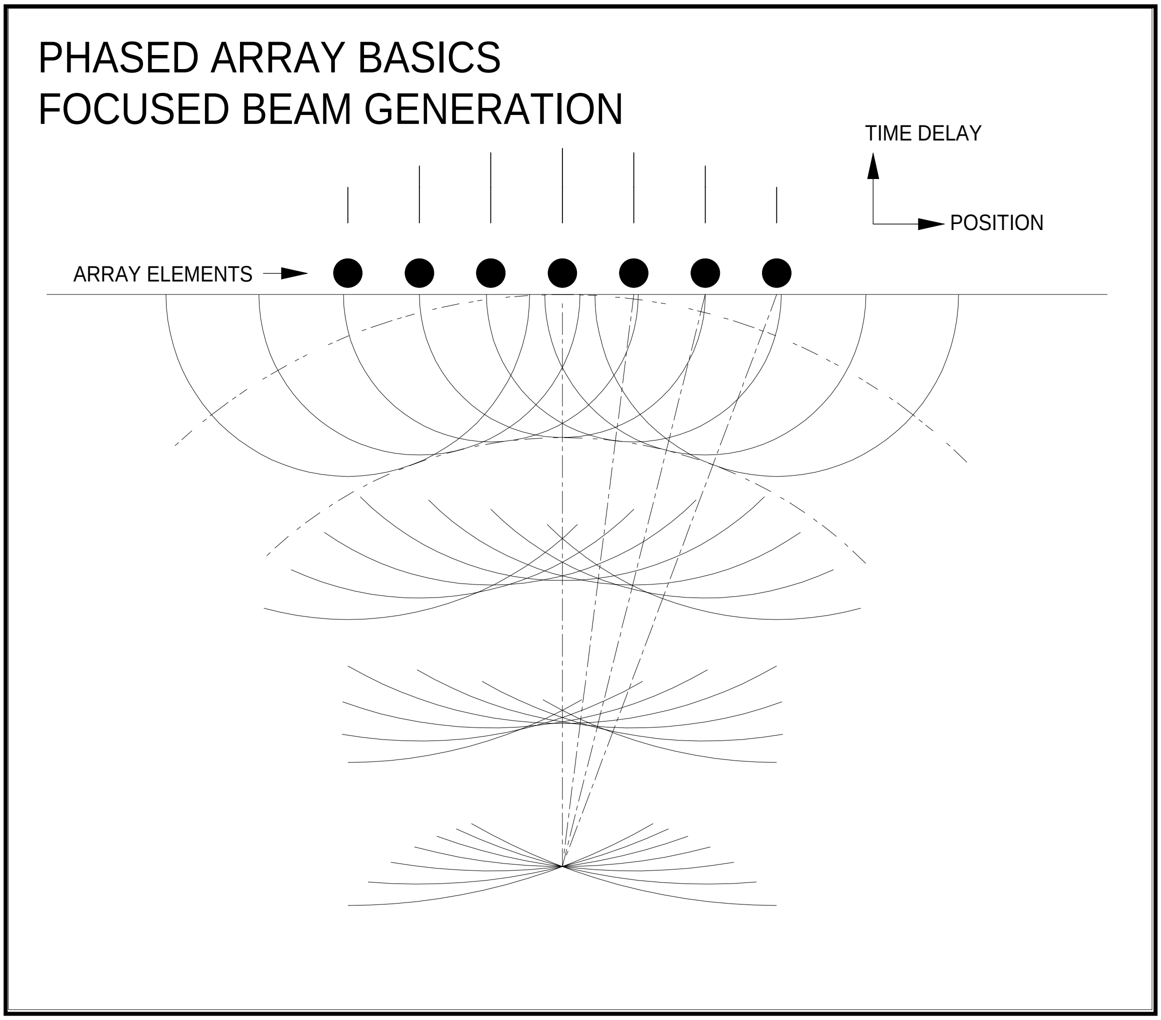


Figure 4 - Illustration of Phased Array Ultrasonic Beam Forming

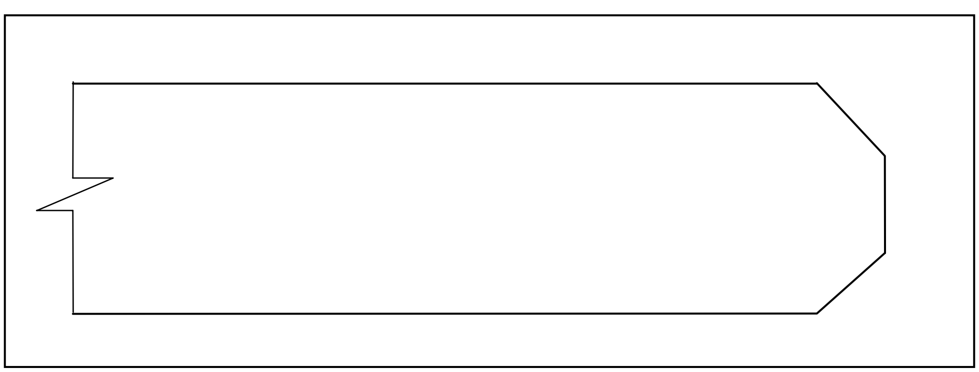


Figure 5 - Typical Prep for Automated Welding of Thick Plate.

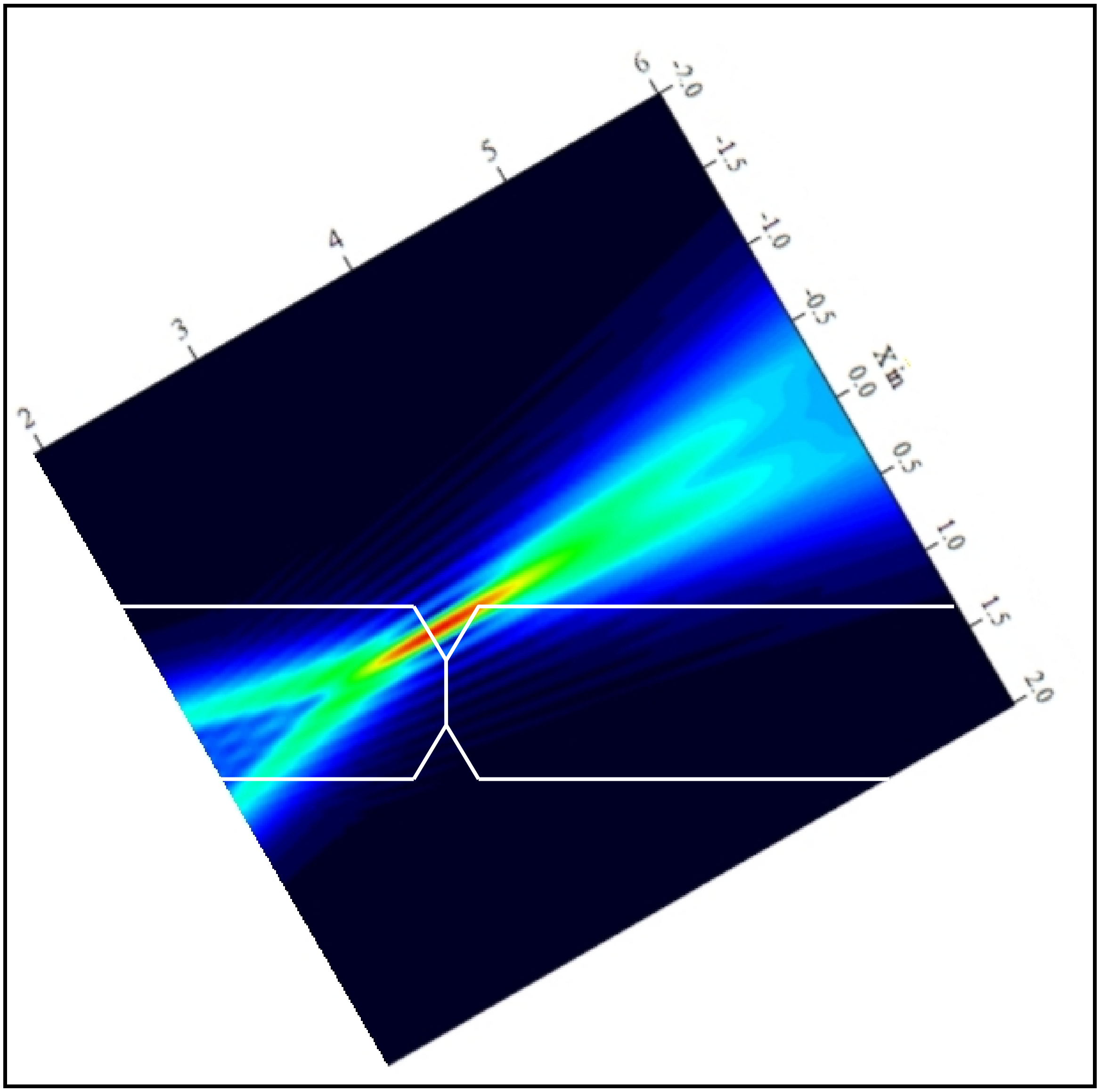


Figure 6 - Simulated Beam Profile for 60º Focused SH Wave.

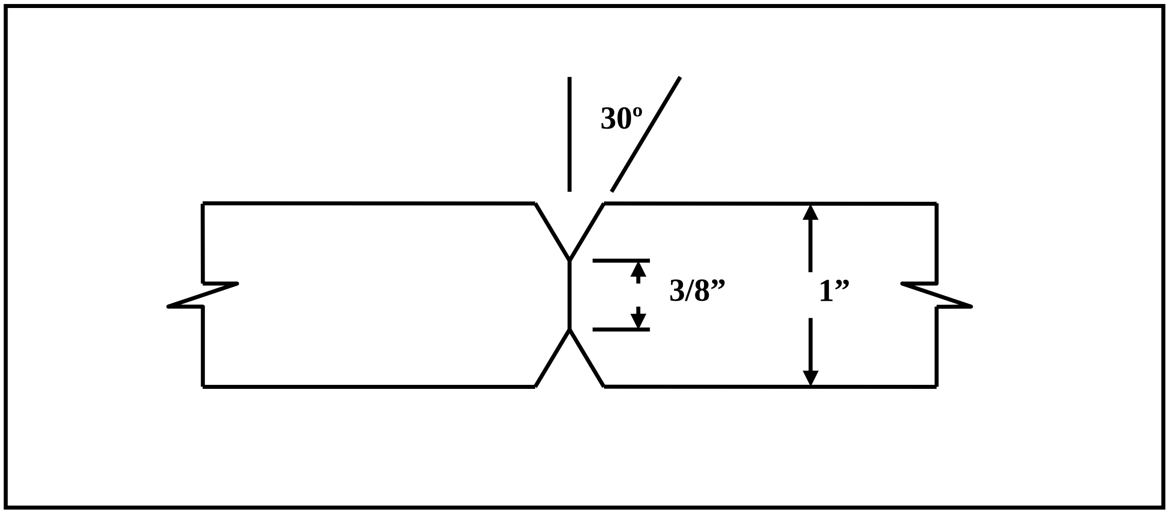


Figure 7 - Weld Joint Diagram

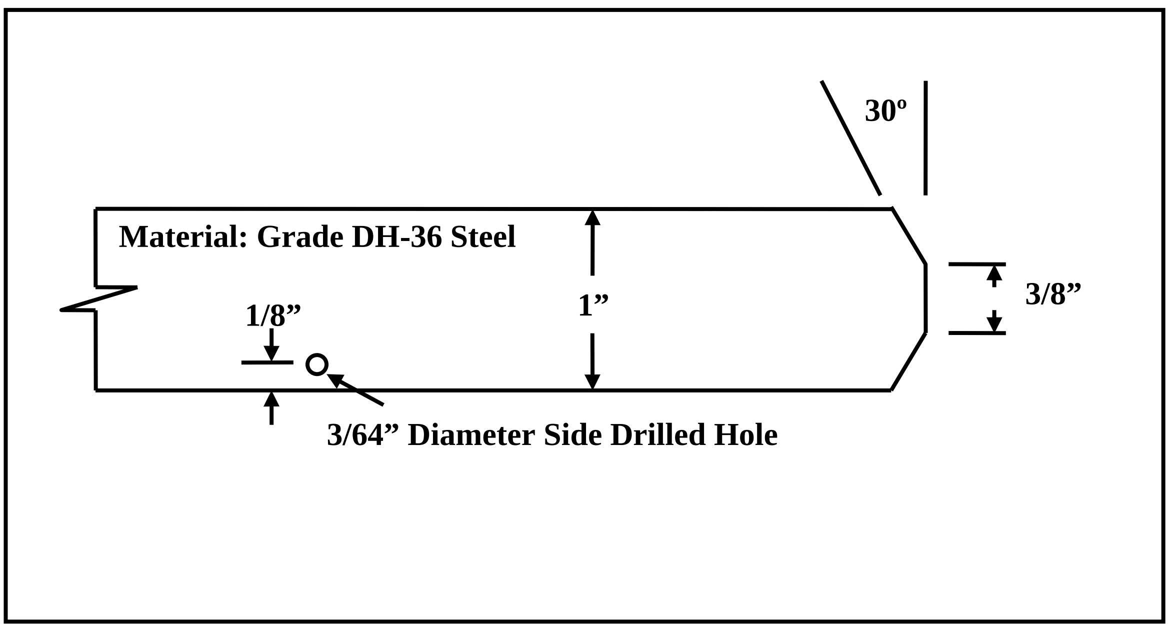


Figure 8 - Calibration Sample NSRP-1 with Weld Prep and 3/64" Side Drilled Hole.

Figure 9 - Phased Array EMAT System

Figure 10 - Computer Control, Data Acquisition, and Display

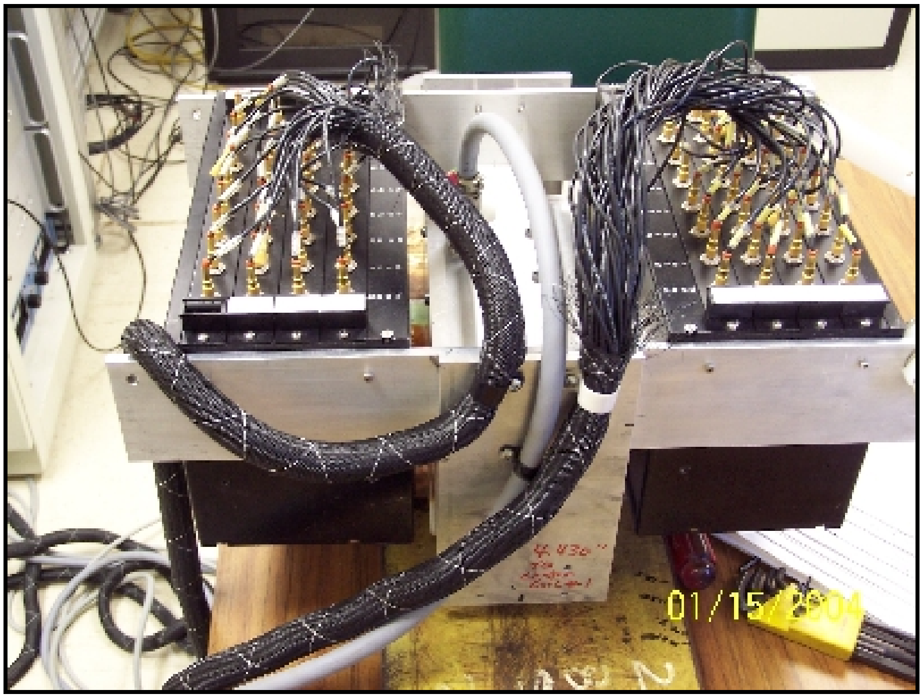


Figure 11 - EMAT Probe Head (Top View)

Figure 12 – EMAT Probe Head (Bottom View)

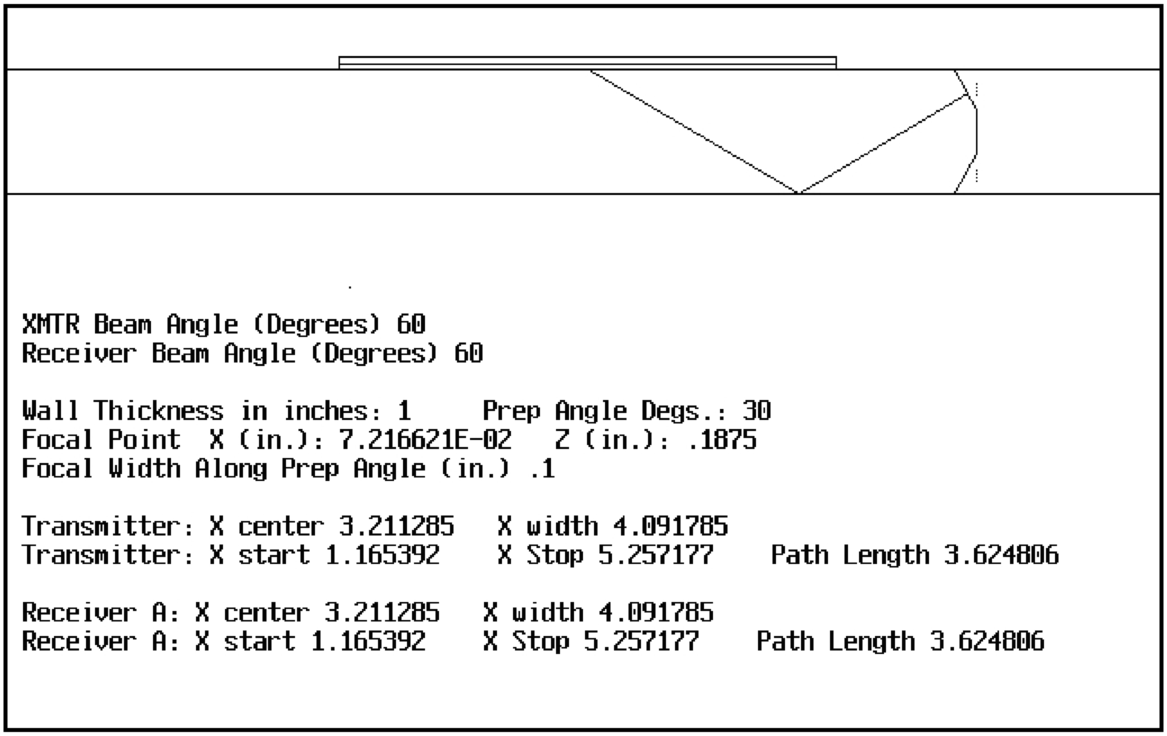


Figure 13 - Parameters for Focusing Beam at Upper Bevel for 1" Thick Plate.

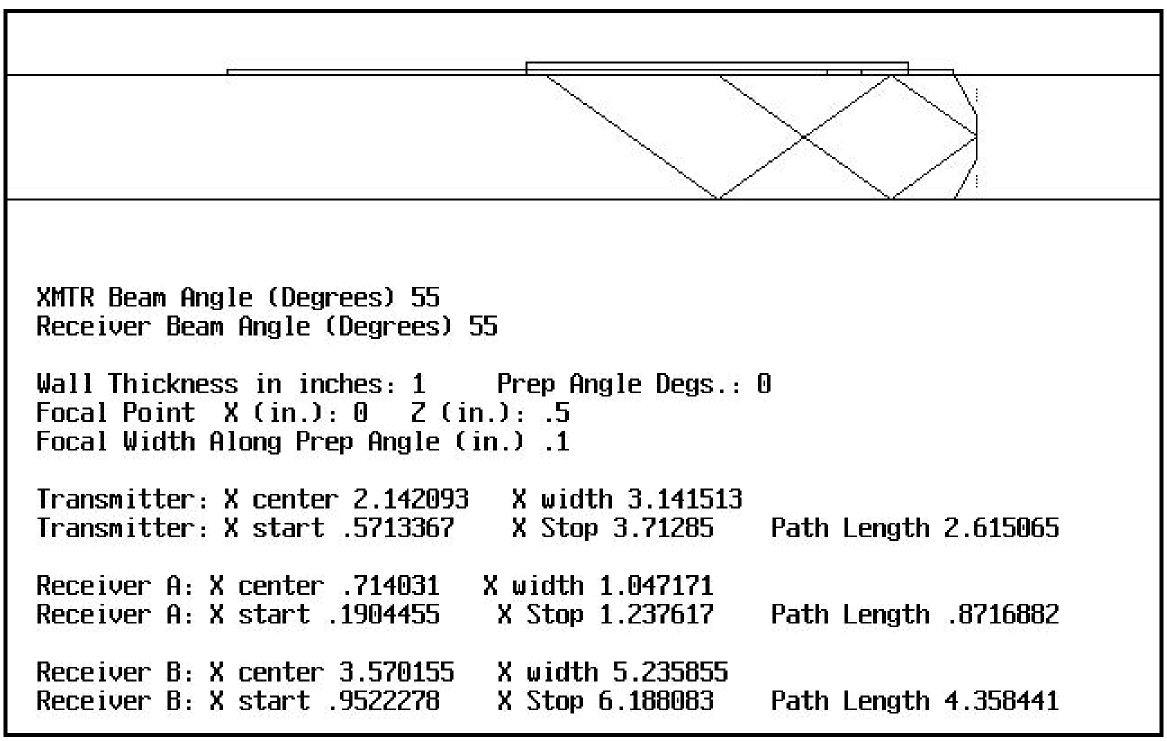


Figure 14 - Parameters for Tandem Operation Inspection of Land

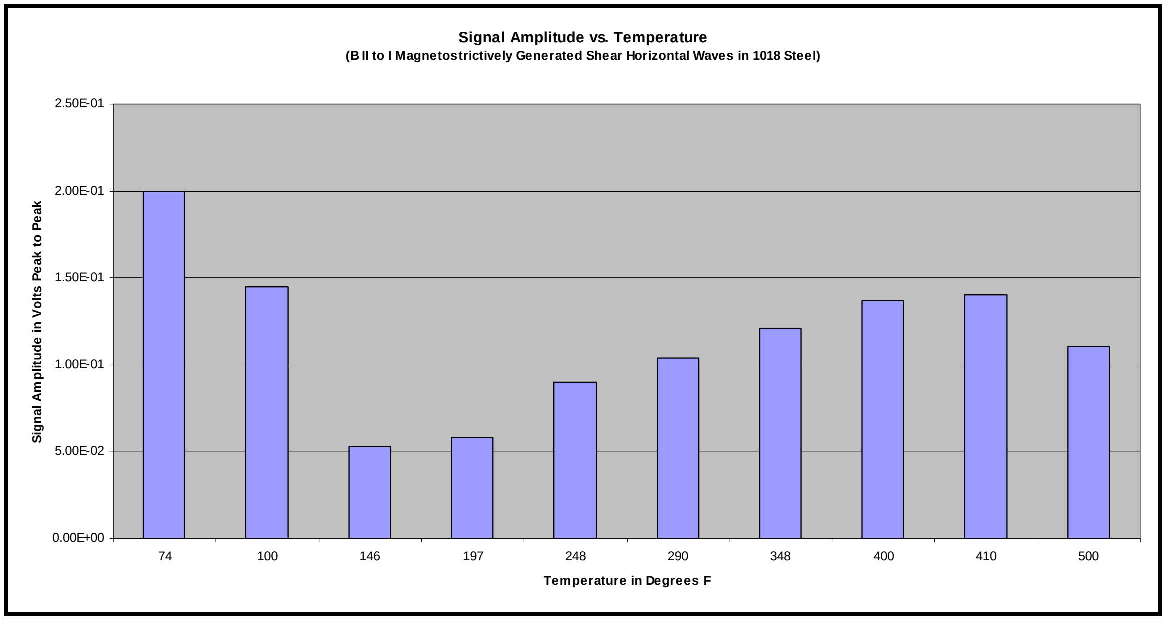


Figure 15 - Signal Amplitude Variation with Temperature for SH Wave EMAT

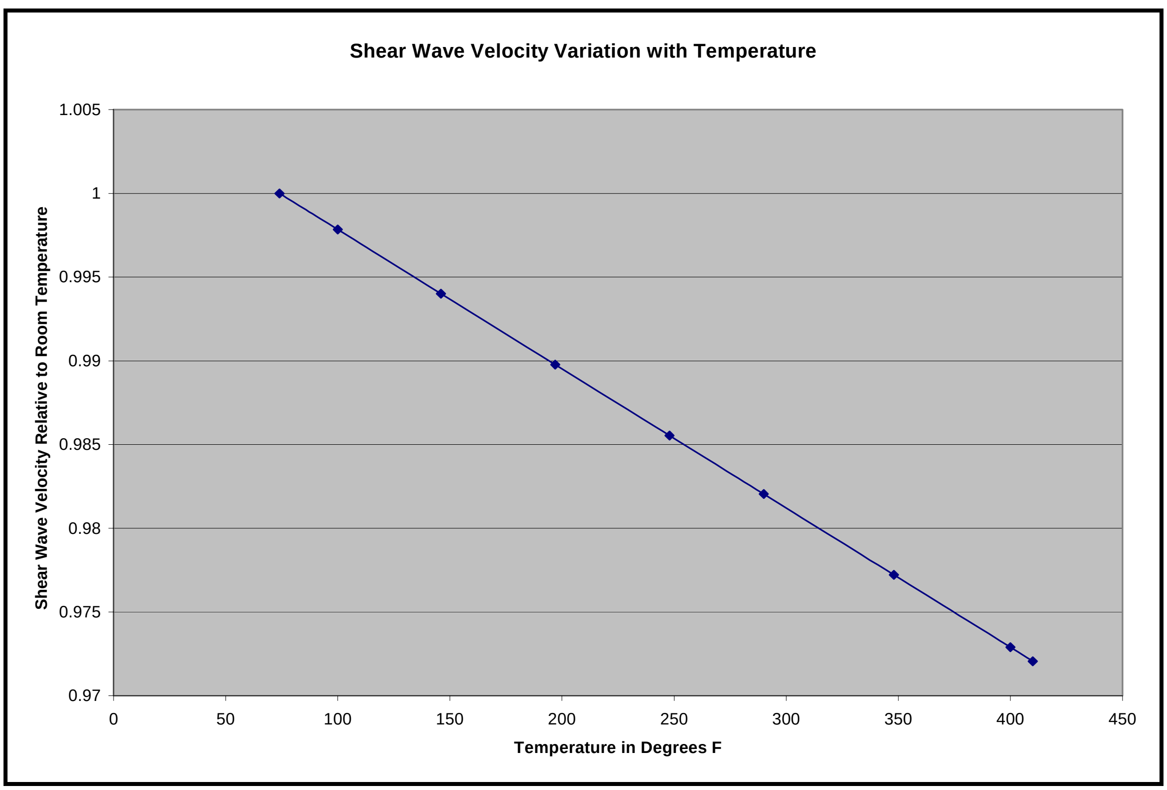


Figure 16 - Calculated Variation in Shear Wave Velocity vs. Temperature

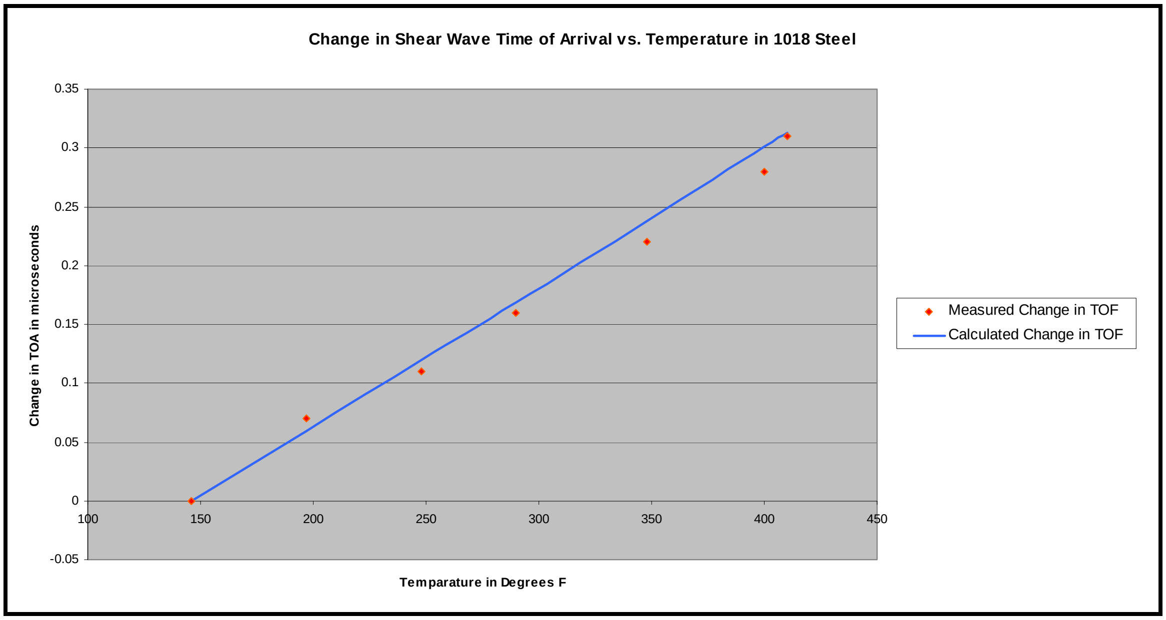


Figure 17 - Measured and Calculated Change in Time of Flight vs. Temperature

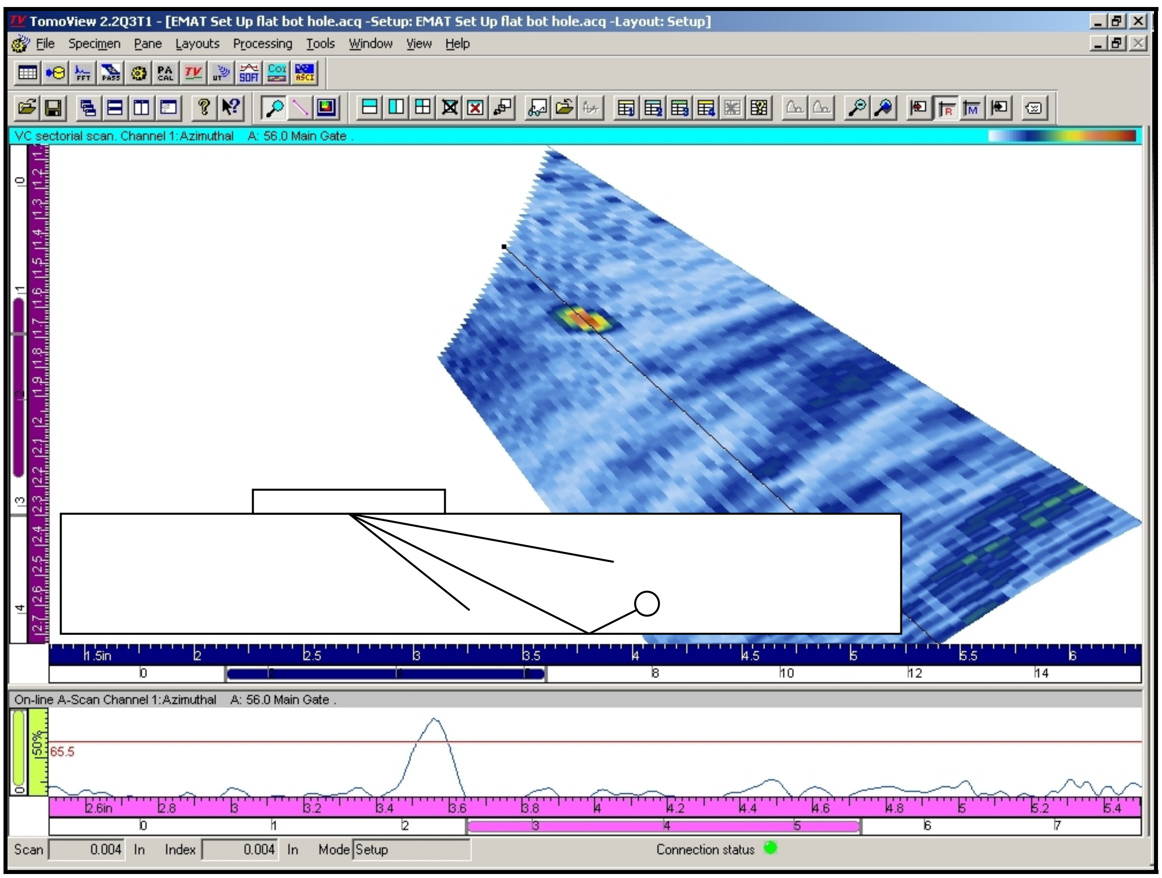


Figure 18 - Image Produced for Angular Sweep of 1/4" Diameter Side Drilled Hole

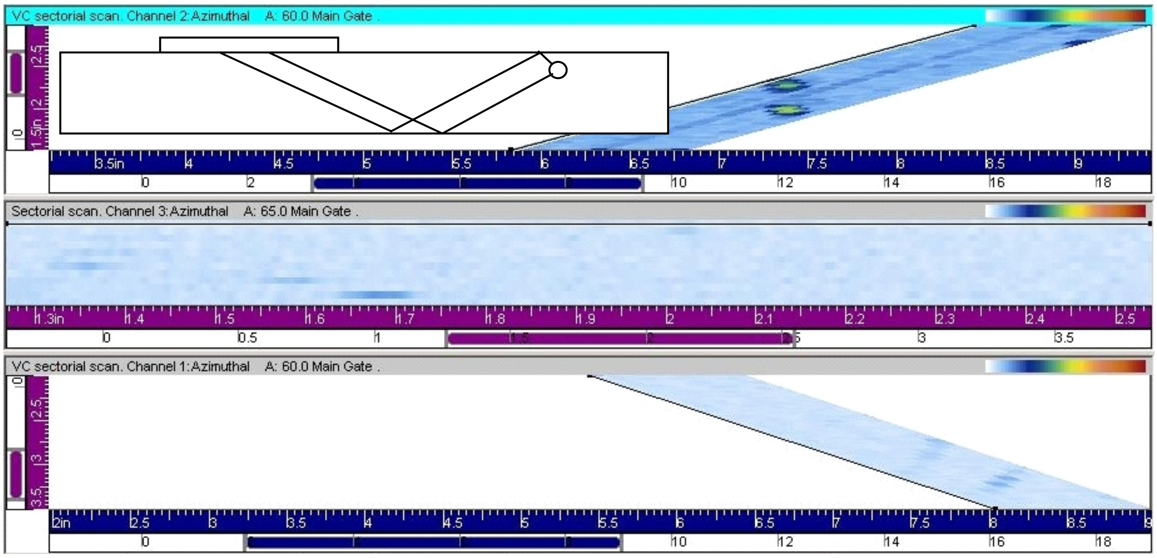


Figure 19 - Image of 3/64s Side Drilled Hole in Cal Block

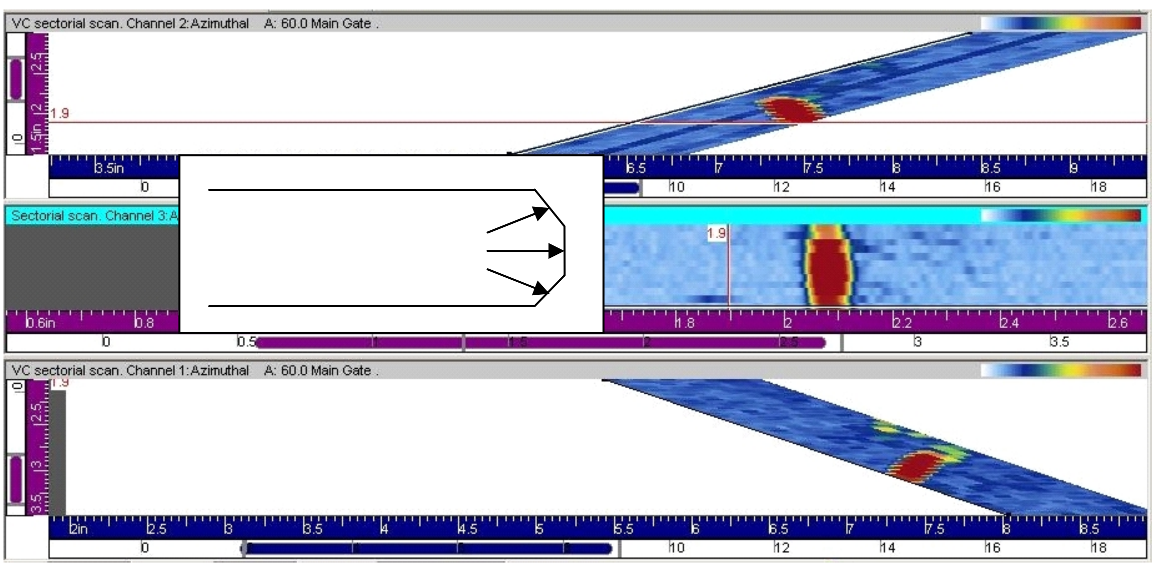


Figure 20 - Image of Reflections from Weld Prep

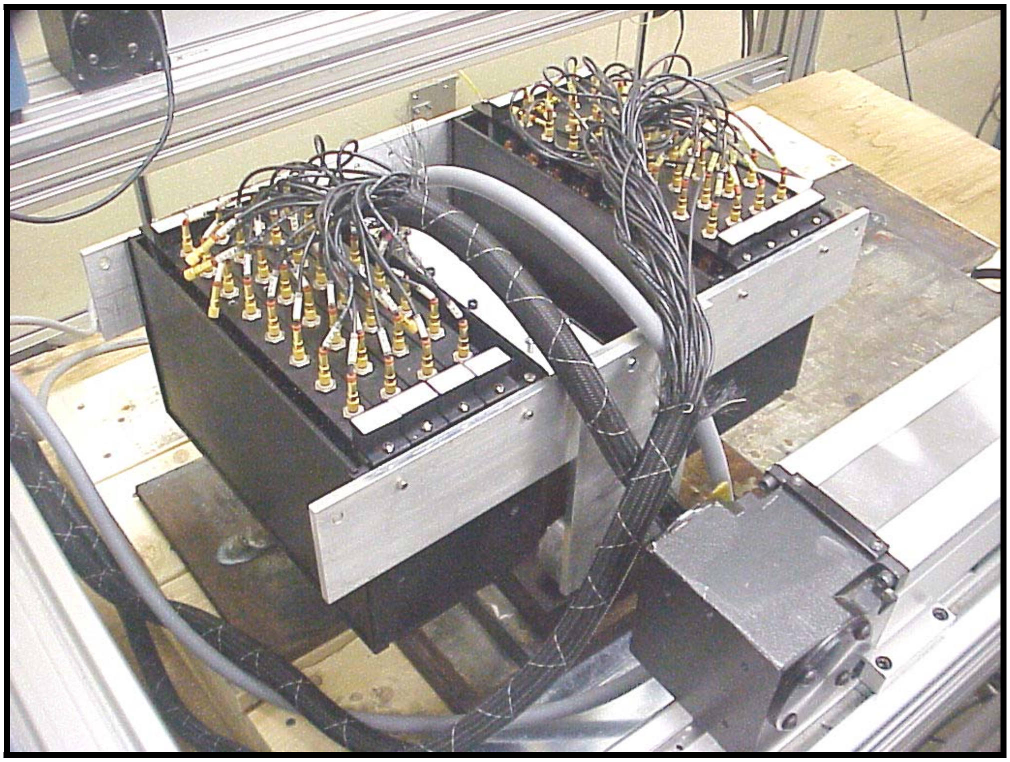


Figure 21 - EMAT Test Head and NGNN Weld Sample 2003-10-1

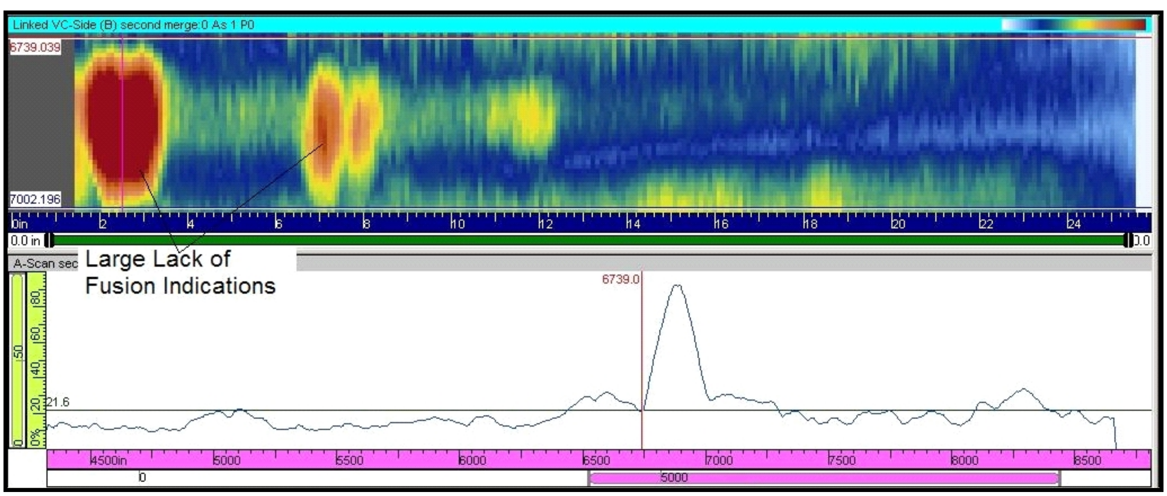


Figure 22 – EMAT Inspection of Vertical Land in NGNN Weld Sample 2003-10-2

Figure 23 - Portable Welder with EMAT Test Head Attached

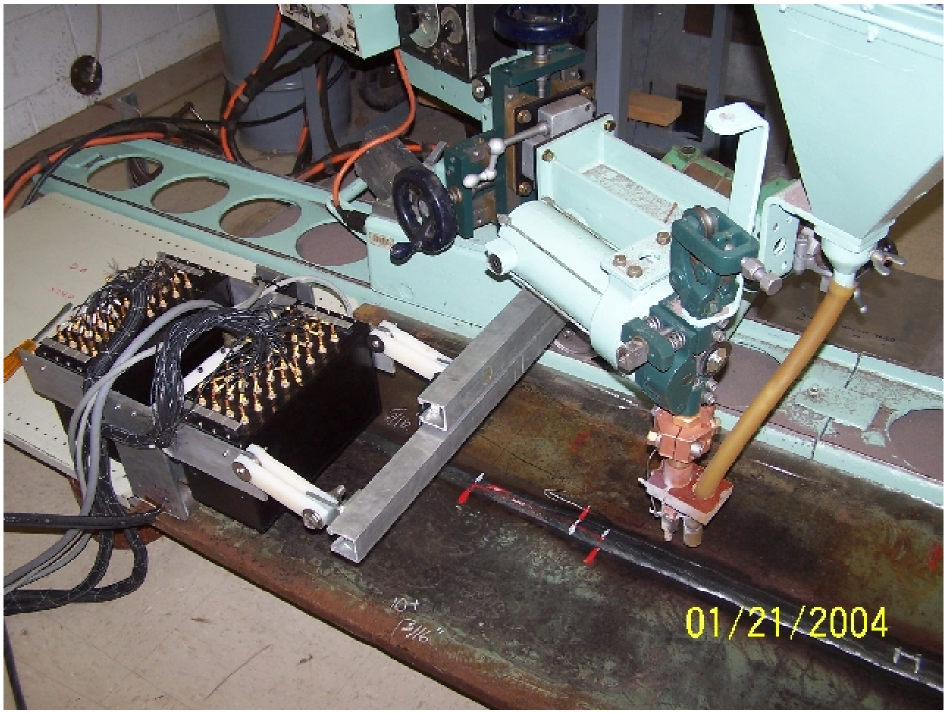


Figure 24 - EMAT Head Attachment to Portable Welder Tractor

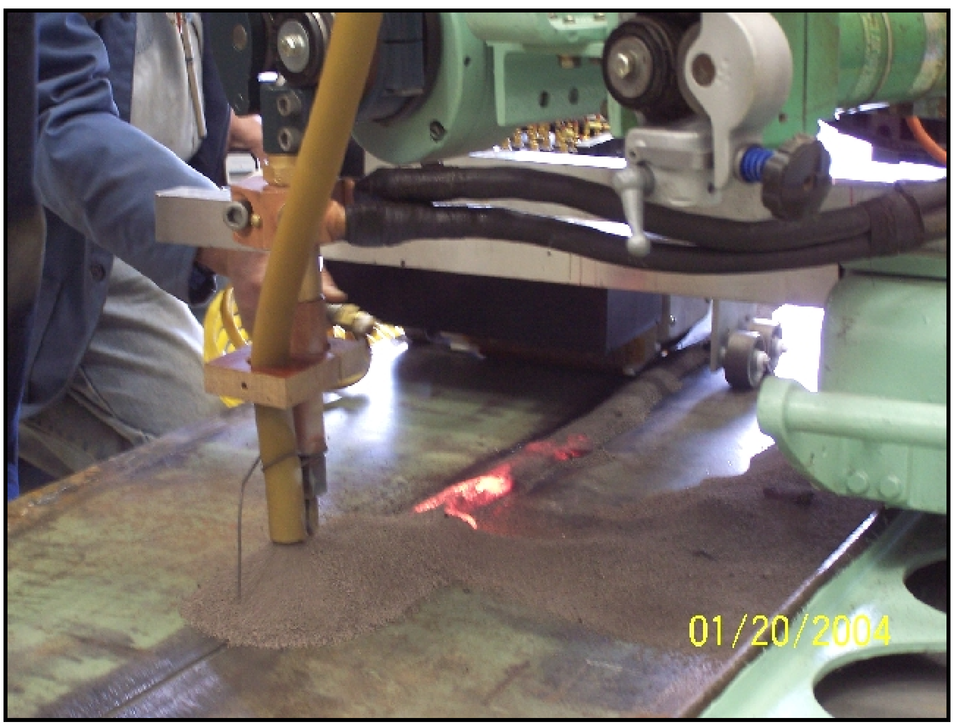


Figure 25 - EMAT Scanning While Welding

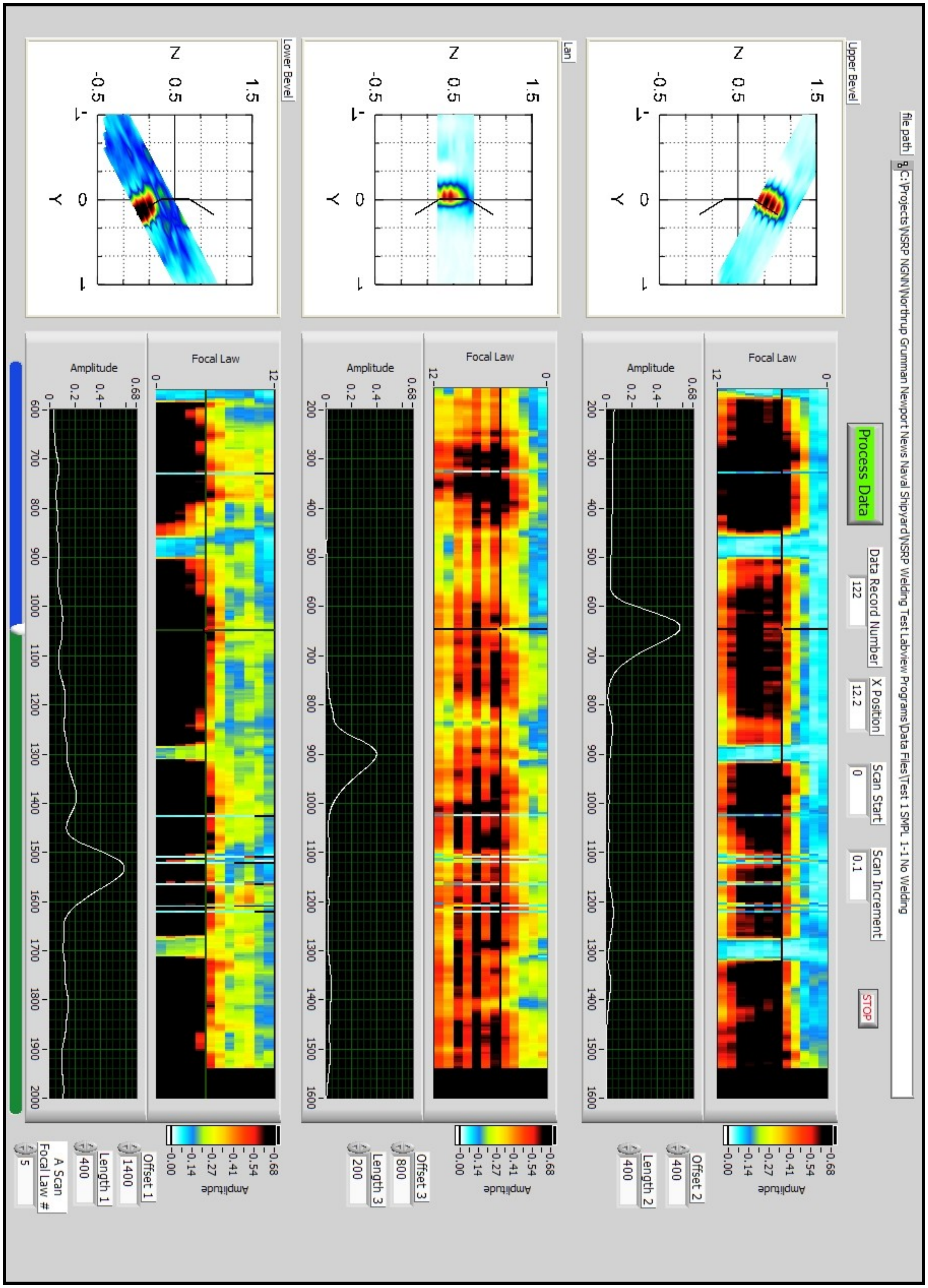


Figure 26 - Weld Sample 1 Side 1 - EMAT Scan Prior to Welding

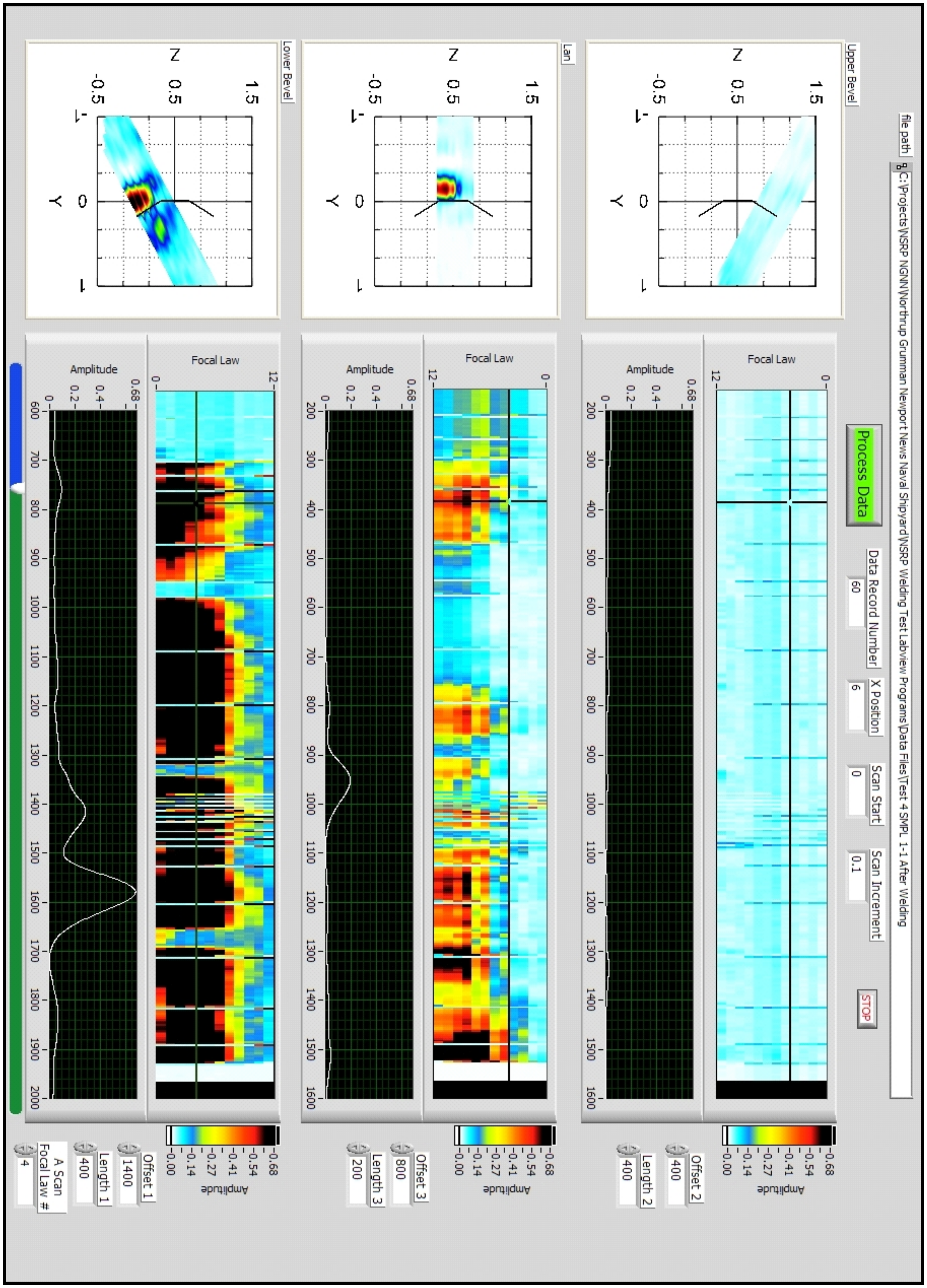


Figure 27 - Weld Sample 1 Side 1 - EMAT Scan After Welding (200º - 300º F)

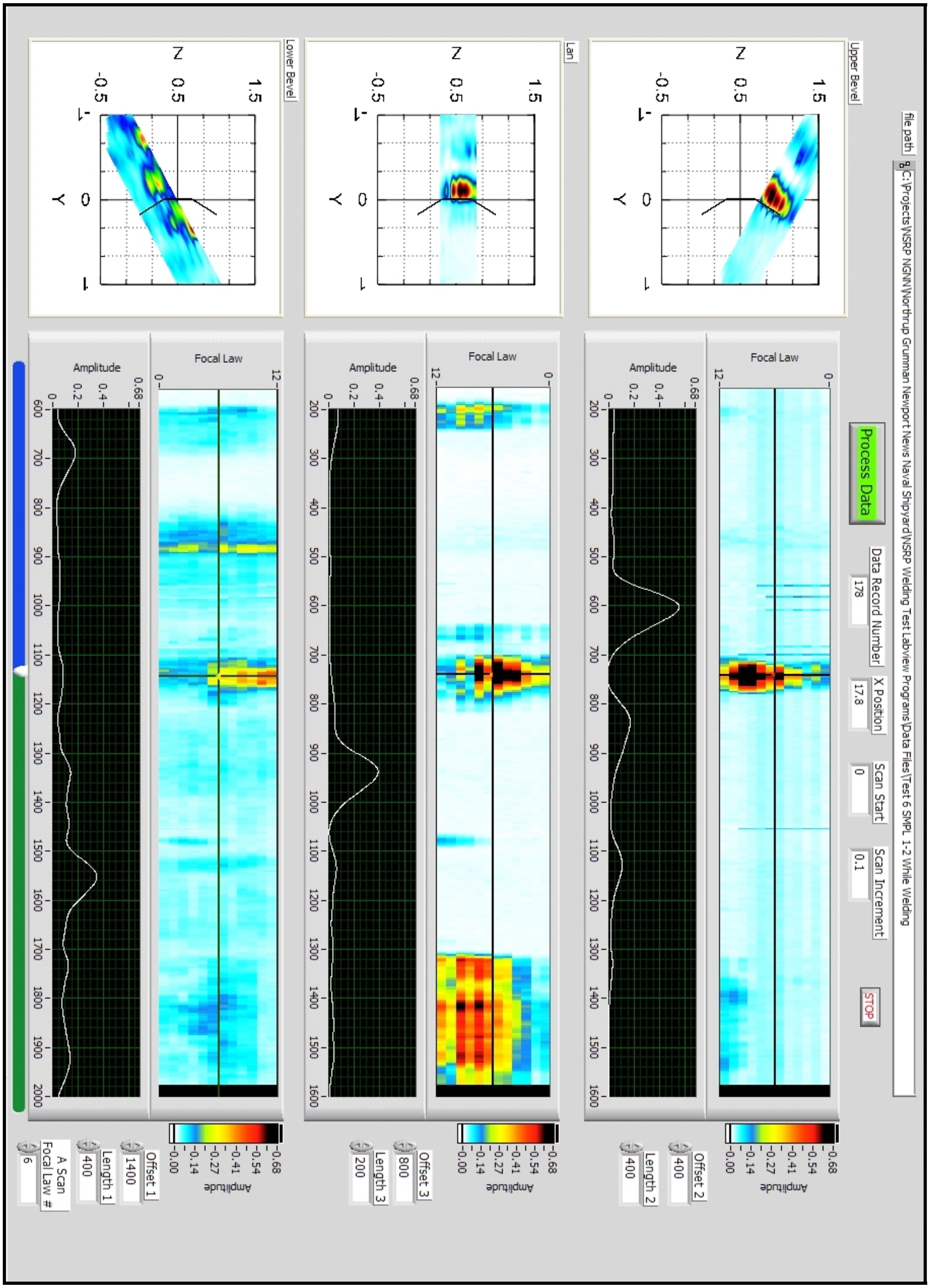


Figure 28 – Weld Sample 1 Side 2 - EMAT Scan While Welding

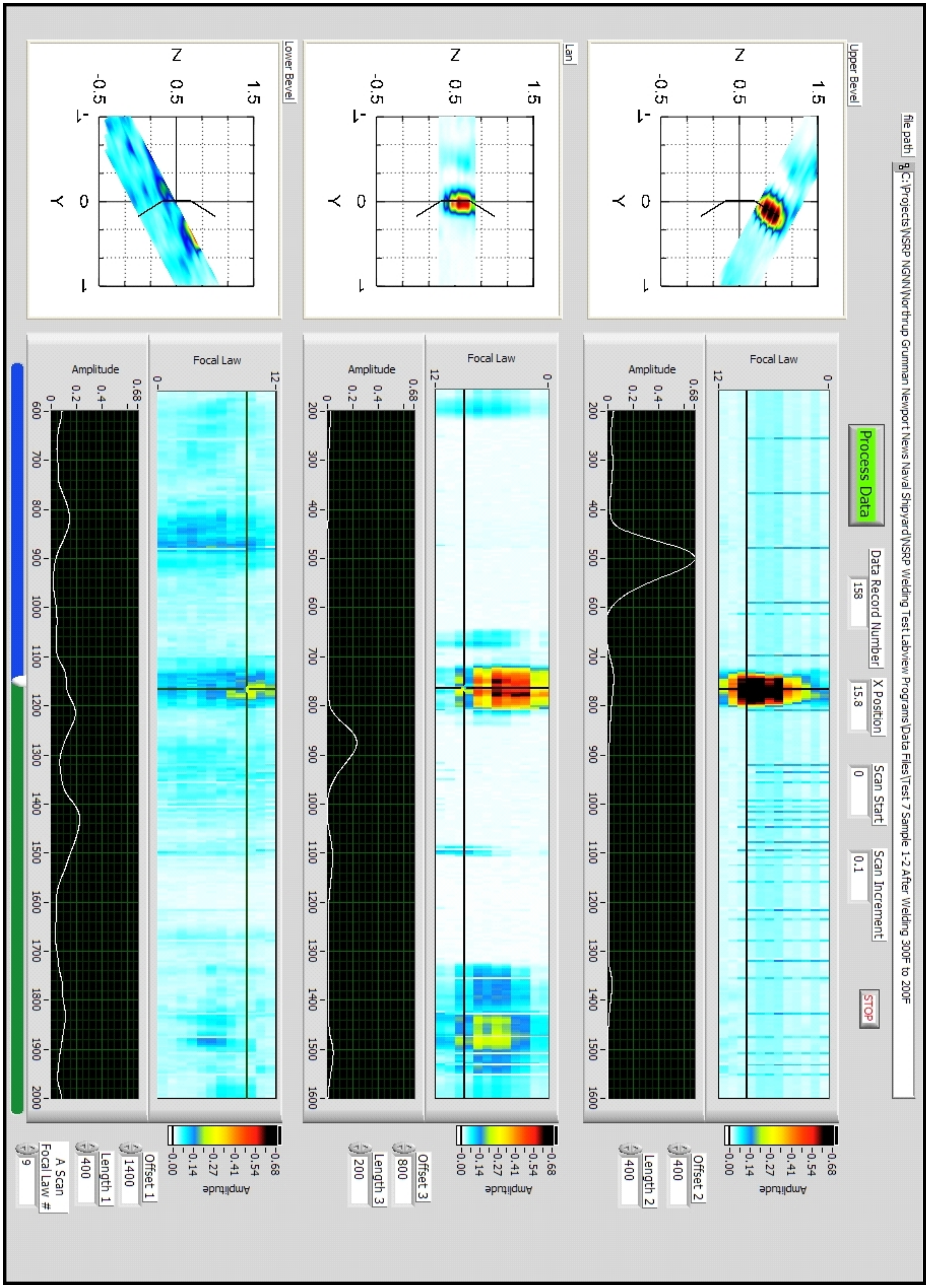


Figure 29 - Weld Sample 1 Side 2 - EMAT Scan after Welding (200º - 300º F)

Figure 30 - Sample 1 Side 2 Photo Showing a Region Where the Torch was Moved off of the Joint.

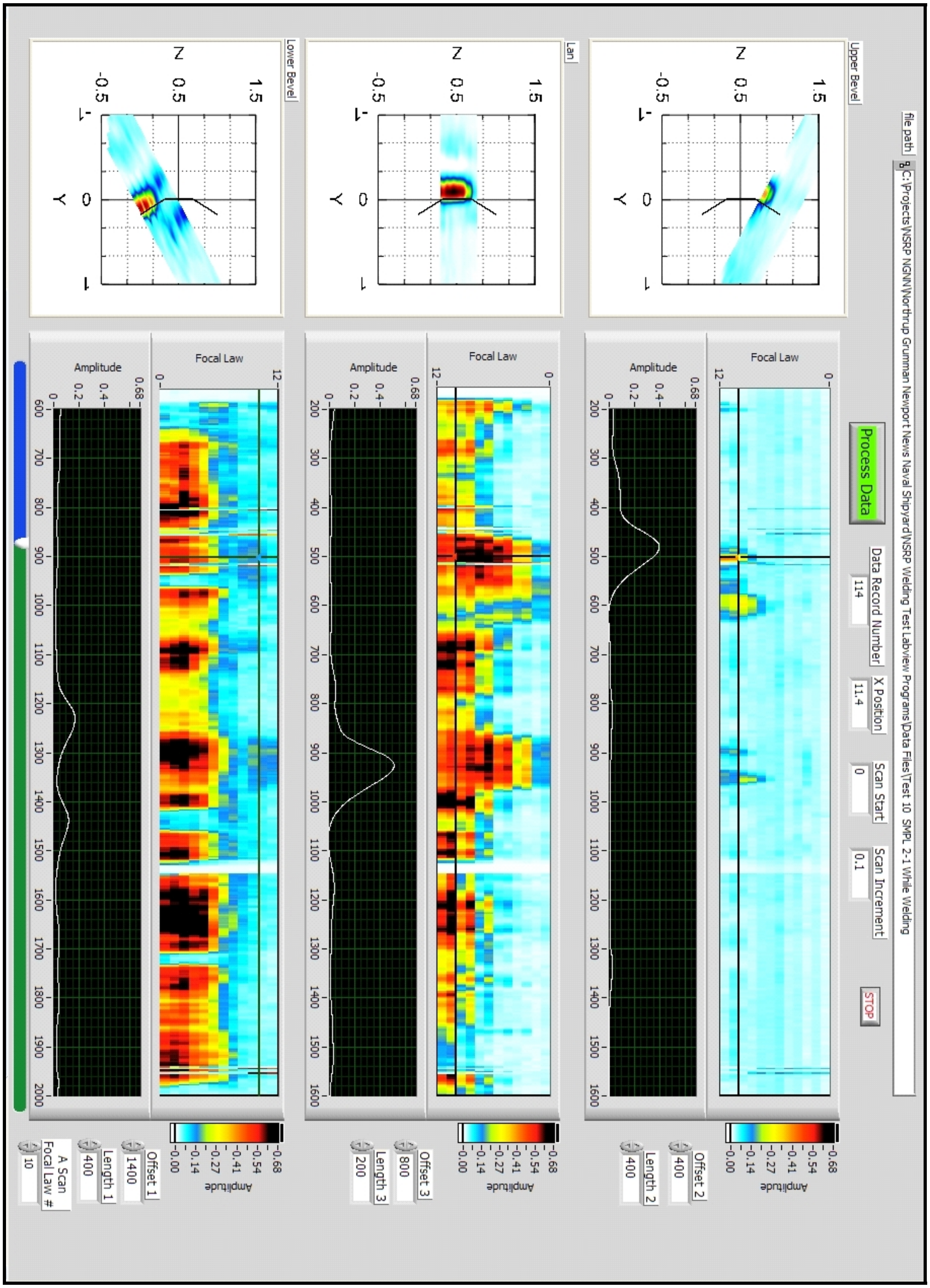


Figure 31 - Weld Sample 2 Side 1 - EMAT Scan While Welding

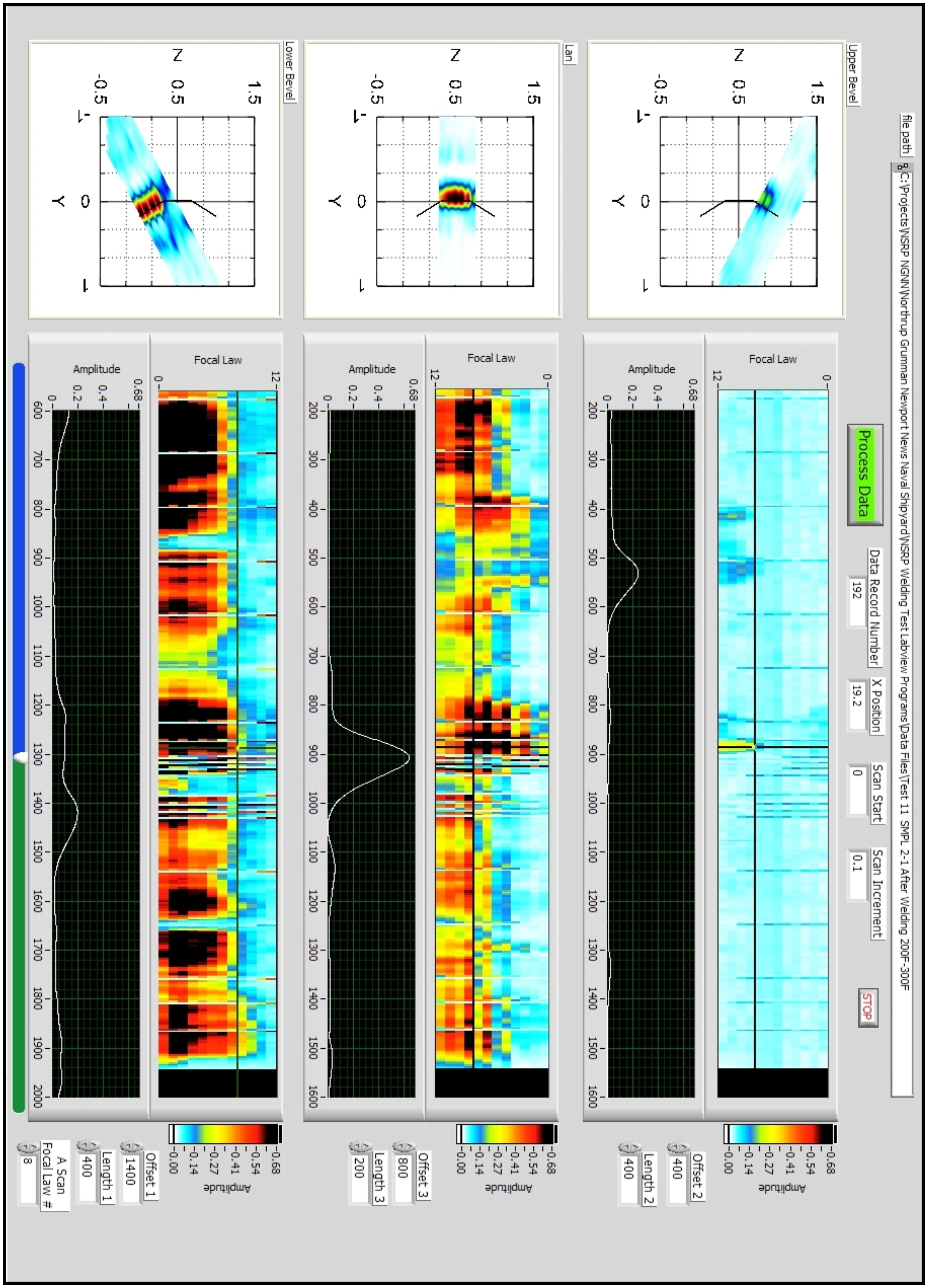


Figure 32 - Weld Sample 2 Side 1 - EMAT Scan After Welding (200º - 300º F)

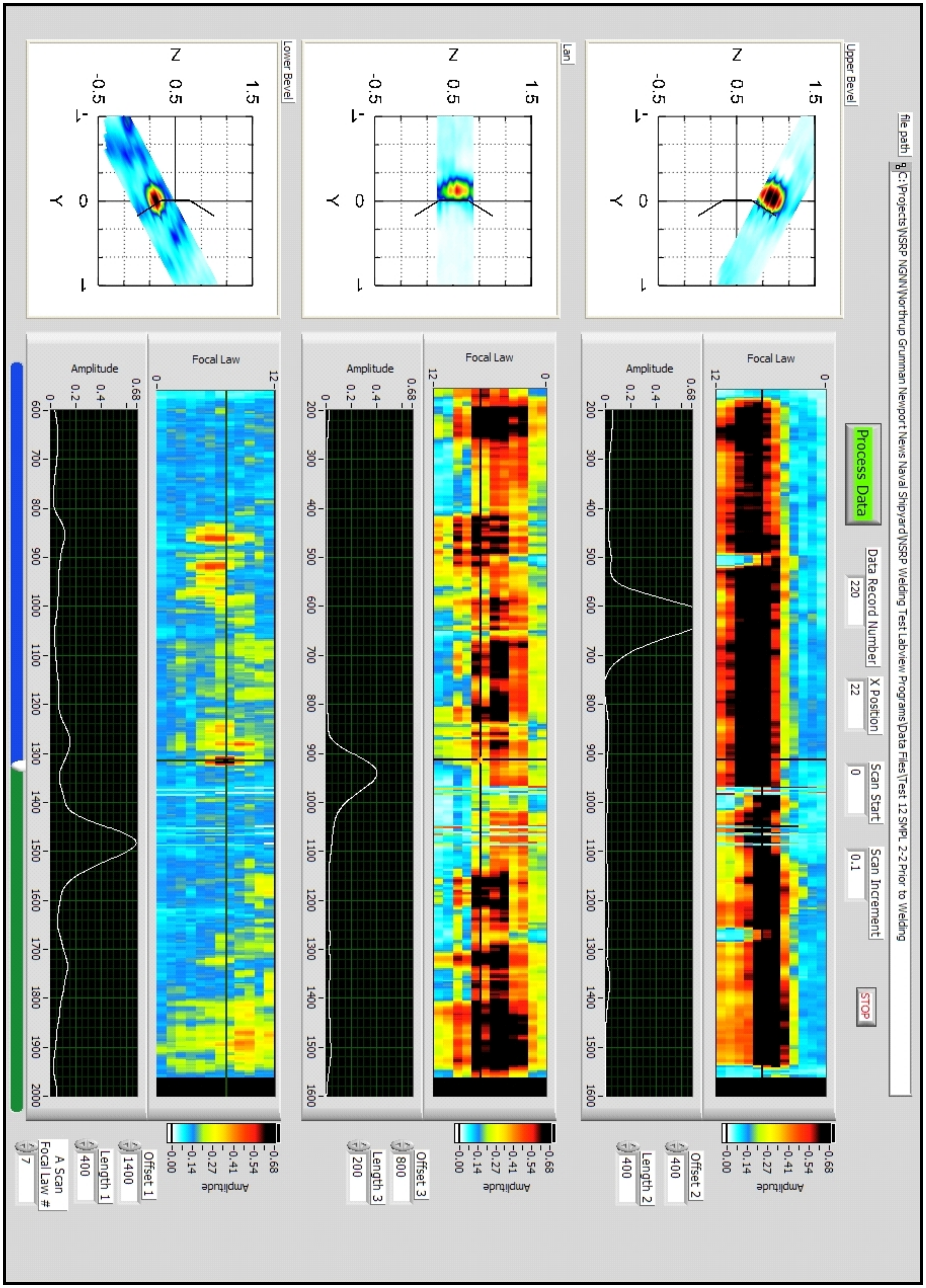


Figure 33 - Sample 2 Side 2 - EMAT Scan Prior to Welding

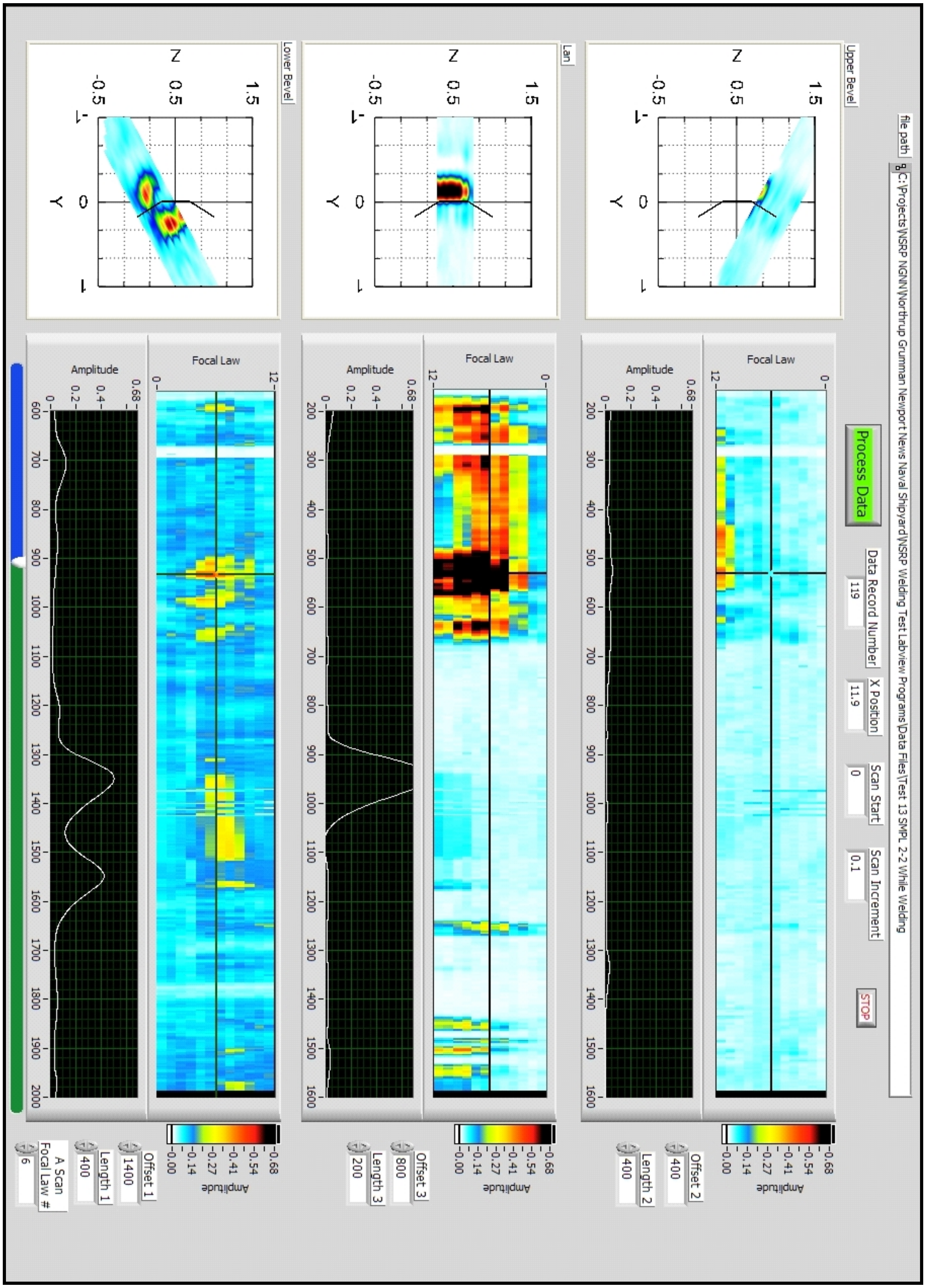


Figure 34 - Weld Sample 2 Side 2 - EMAT Scan While Welding

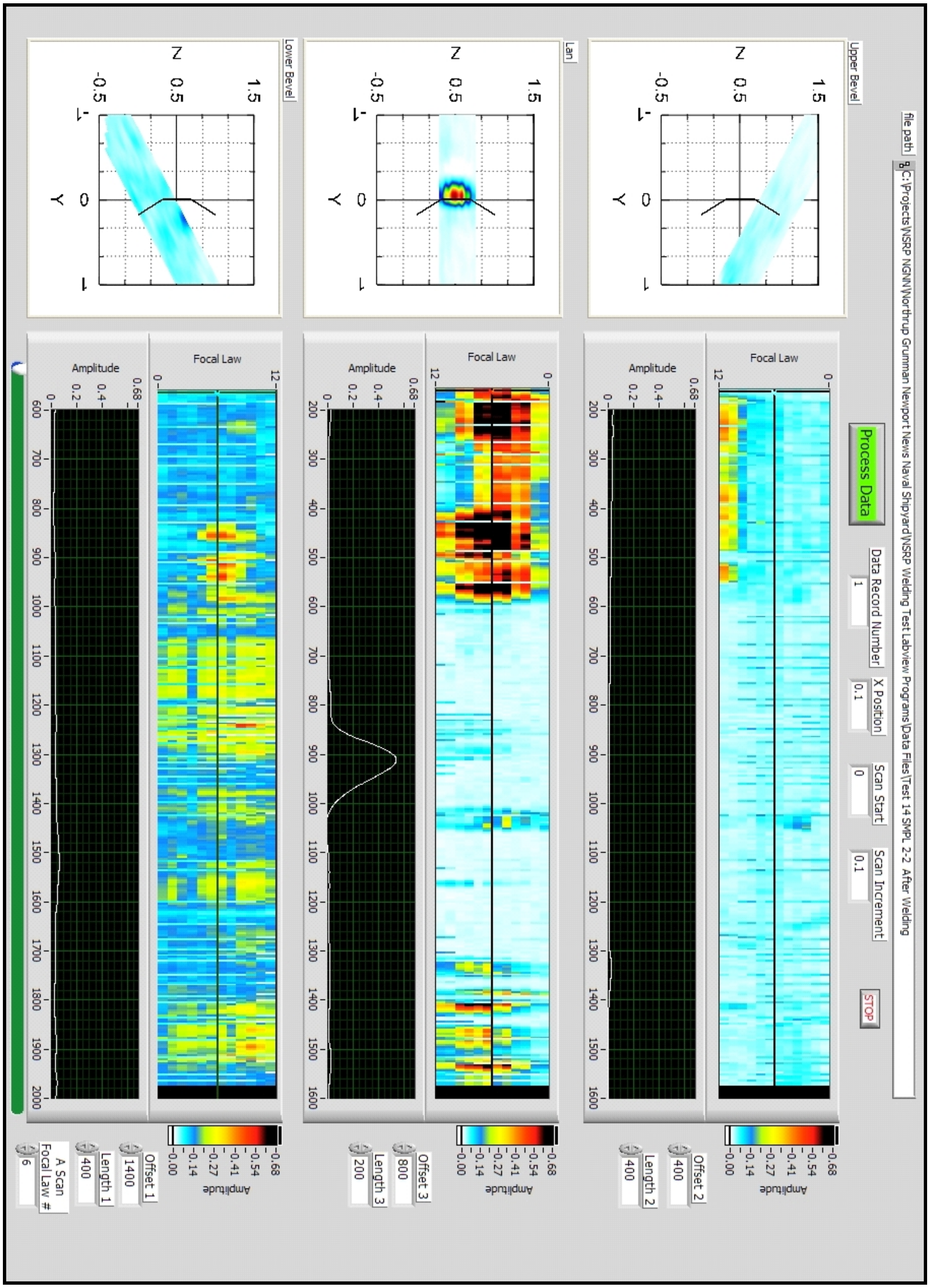


Figure 35 - Weld Sample 2 Side 2 - EMAT Scan After Welding (200º - 300º F)

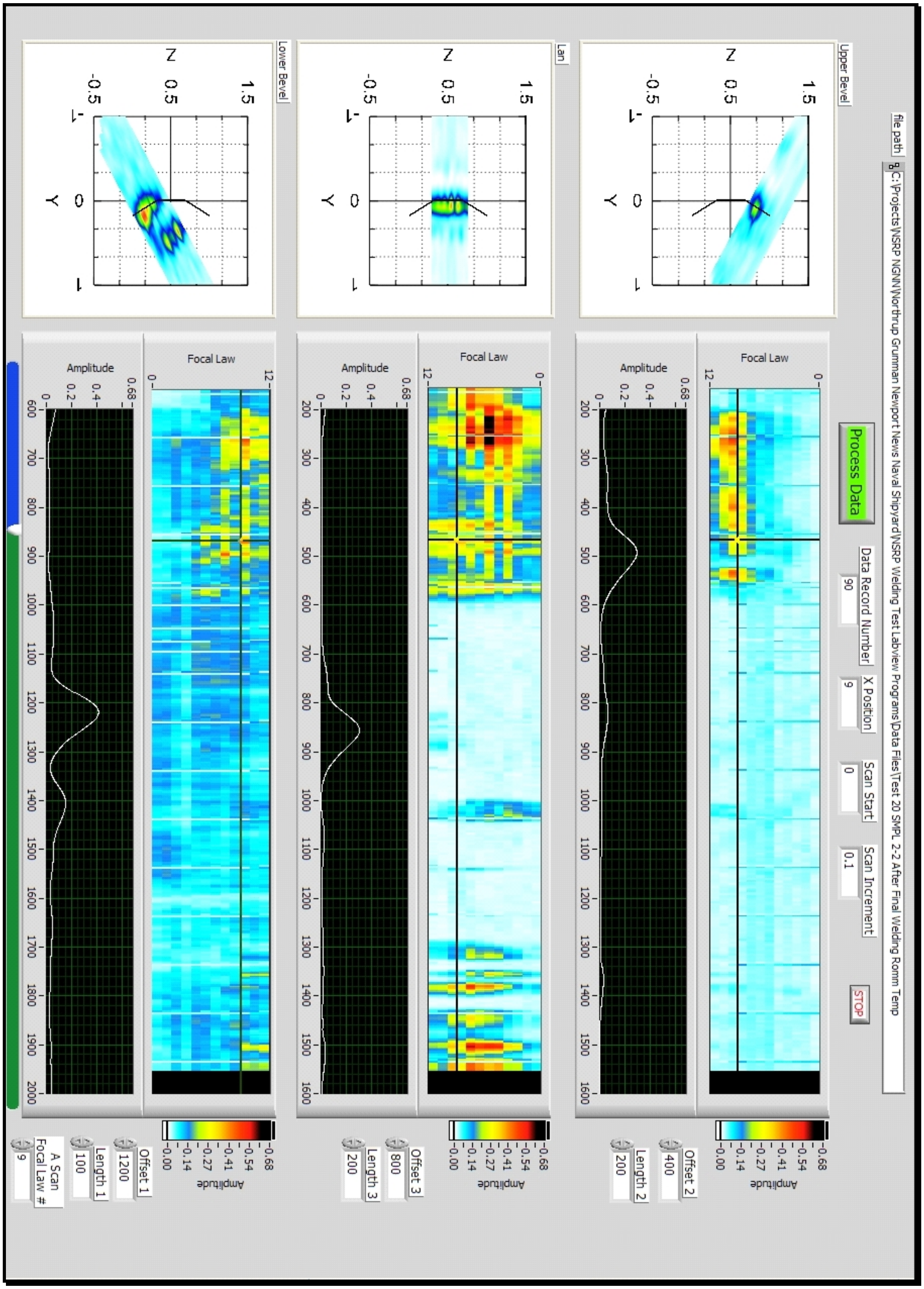
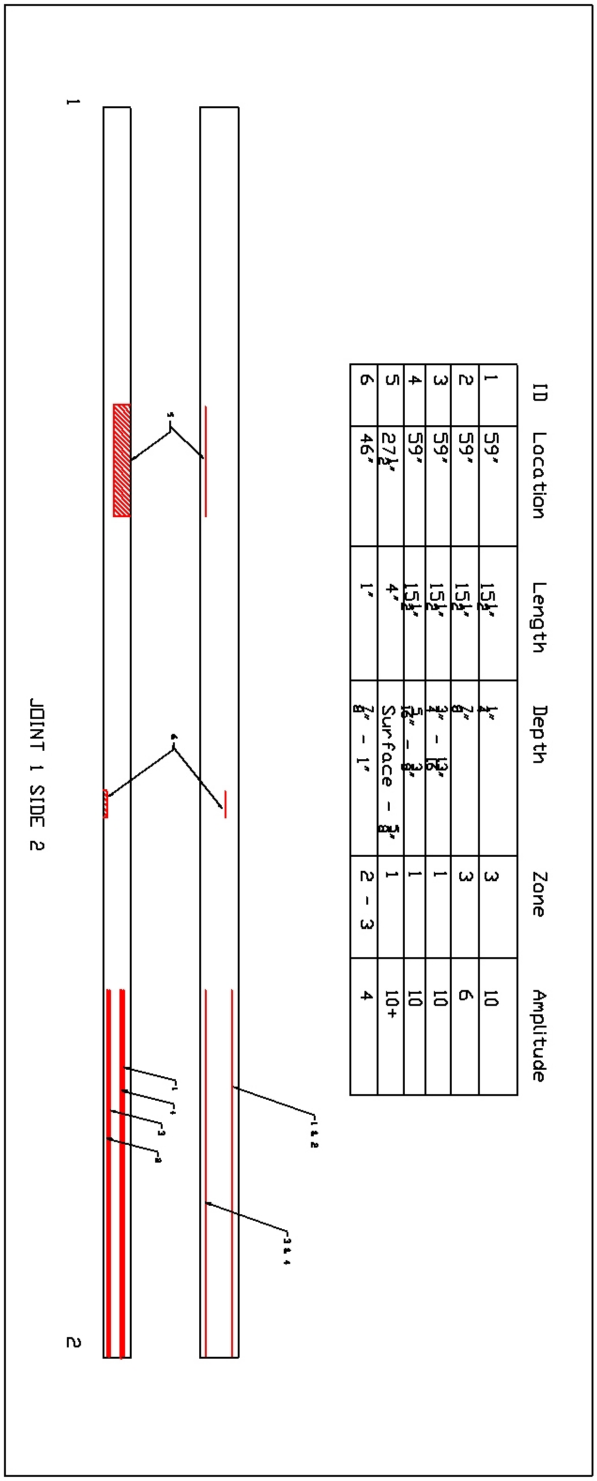


Figure 36 - Weld Sample 2 Side 2 - EMAT Scan After Welding (Room Temp.)



ID	Location	Length	Depth	Zone	Amplitude
1	59"	15½"	¼"	3	10
2	59"	15½"	⅞"	3	6
3	59"	15½"	¾" – 13/16"	1	10
4	59"	15½"	5/16" – ⅜"	1	10
5	27½"	4"	Surface – ⅜"	1	10+
6	46"	1"	⅞" – 1"	2 – 3	4

Figure 37 - Sample 1 Hand Held UT Flaw Map Prepared by NGNN UT Inspectors (Not to Scale)

ID	Location	Length	Depth	Zone	Amplitude
1	0"	23 1/2"	5/16"	3	10+
2	16 3/4"	8 1/2"	13/16"	2	10+
3	41 1/2"	1"	3/4"	3	3
4	48 3/4"	1 1/2"	5/16" – 3/8"	2	5
5	64 1/4"	2"	11/16" – 3/4"	3	3
6	67 1/2"	1"	5/16" – 3/8"	3	3
7	68"	12"	3/4"	2	4
8	70 1/2"	1"	1/8"	3	2
9 *	4 3/4"	2 1/2"	3/4"	2	3
10 *	4"	23 1/2"	1/4" – 3/8"	2	10+
11 *	41 1/2"	2"	7/8"	1	10+

* These indications were detected from opposite side of weld. (opposite of EMAT)

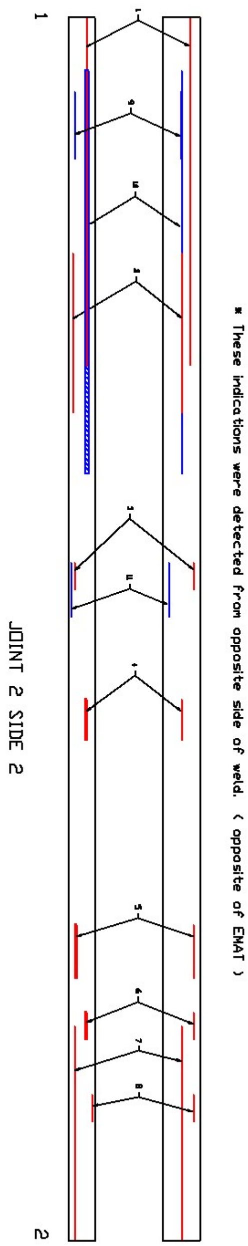
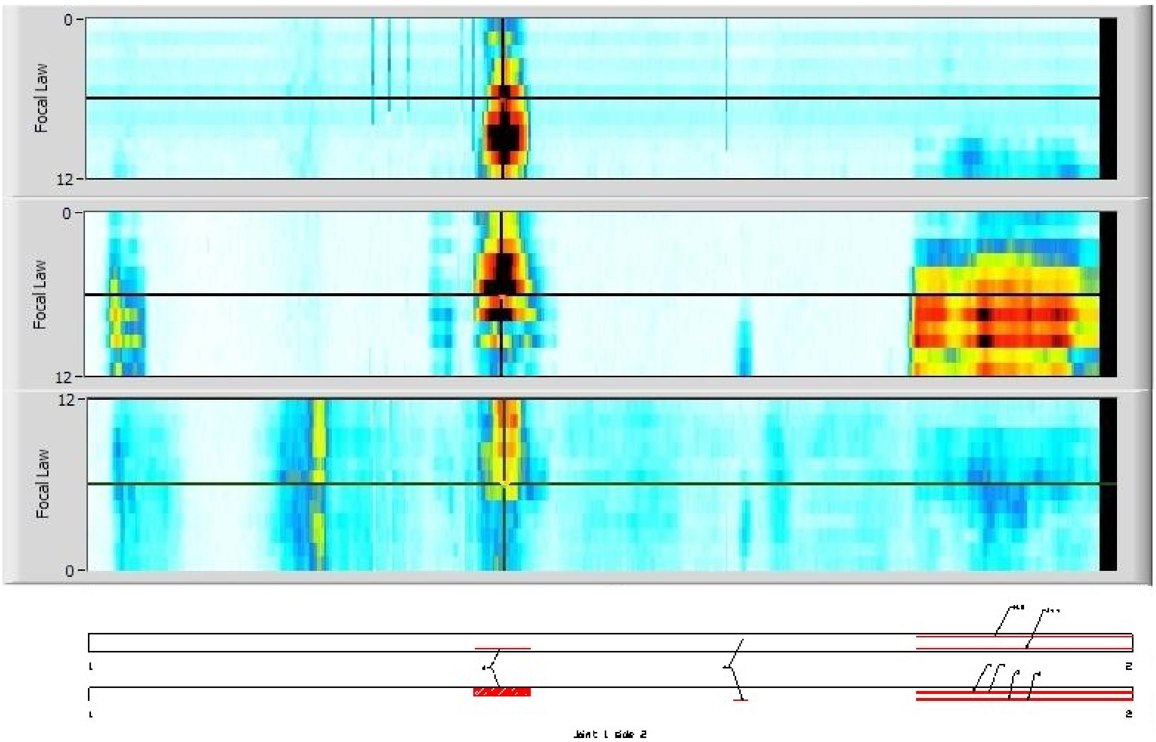
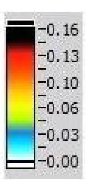


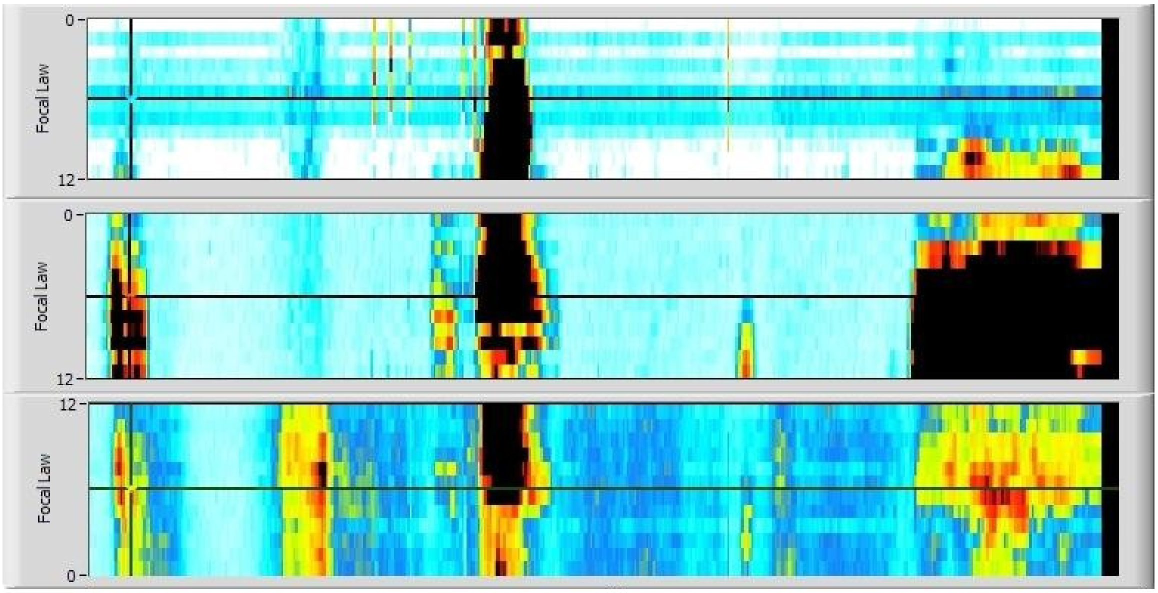
Figure 38 - Sample 2 Hand Held UT Flaw Map Prepared by NGNN UT Inspectors (Not to Scale)

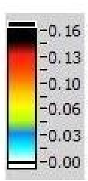




Location	Length	Depth	Zone	Amplitude
59"	15½"	½"	3	10
59"	15½"	7/8"	3	6
59"	15½"	3/4" - 13/16"	1	10
59"	15½"	3/16" - 3/8"	1	10
27½"	4"	Surface - 5/8"	1	10+
46"	1"	7/8" - 1"	2 - 3	4

Figure 39 - Sample 1 Comparison of EMAT Response to UT Flaw Map – Low Gain





Location	Length	Depth	Zone	Amplitude
59"	15½"	¼"	3	10
59"	15½"	⅞"	3	6
59"	15½"	¾" - 13/16"	1	10
59"	15½"	3/16" - ⅜"	1	10
27½"	4"	Surface - ⅜"	1	10+
46"	1"	⅞" - 1"	2 - 3	4

Figure 40 - Sample 1 Comparison of EMAT Response to UT Flaw Map - High Gain

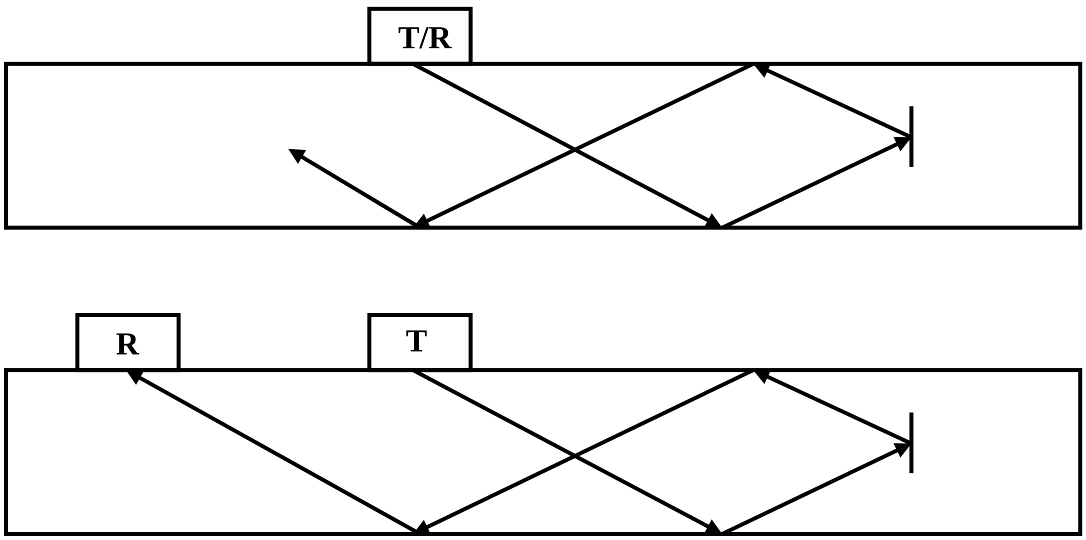


Figure 41 - Inspection of Land Using Hand Held UT (Upper) and EMAT (Lower)

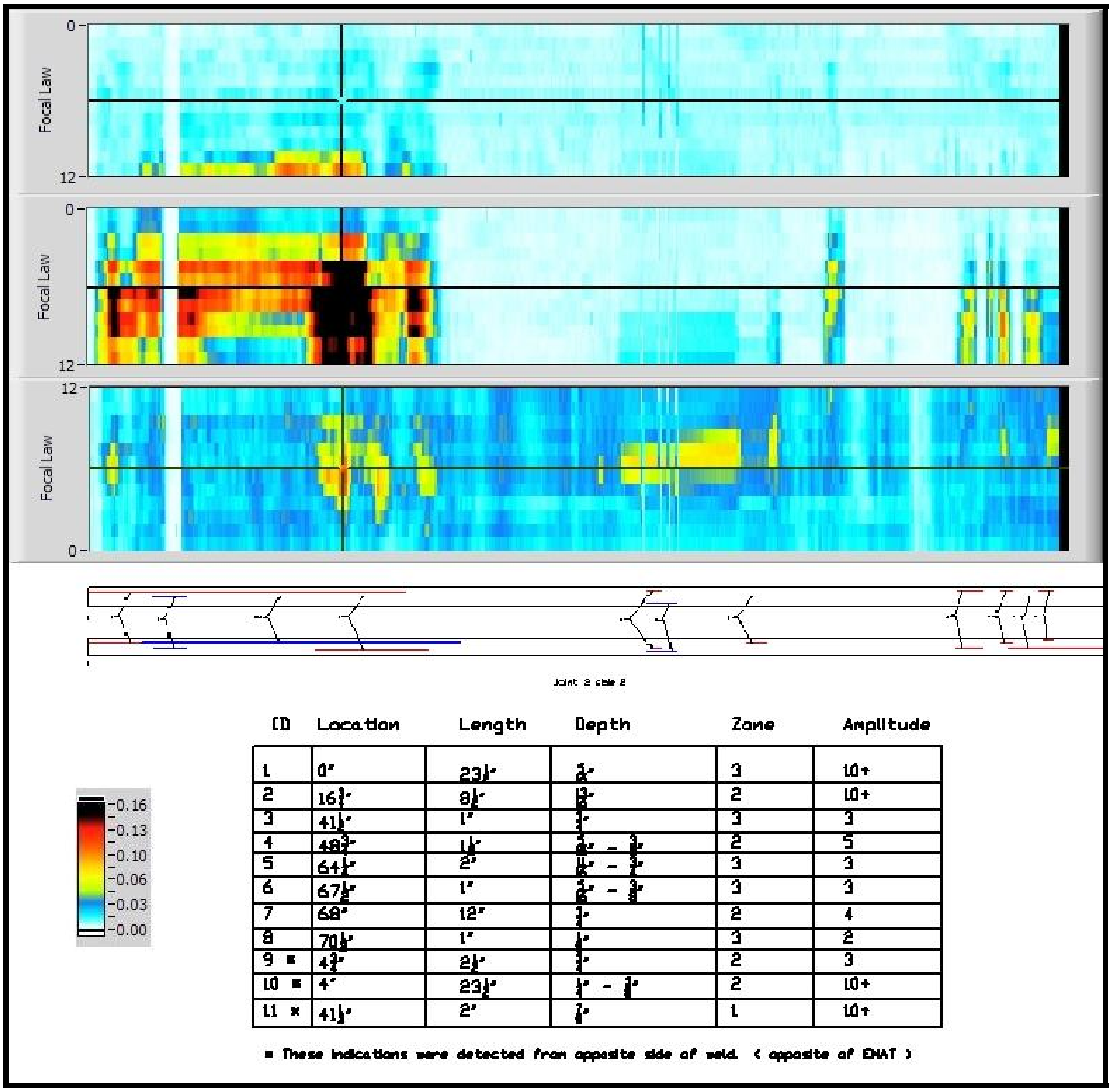
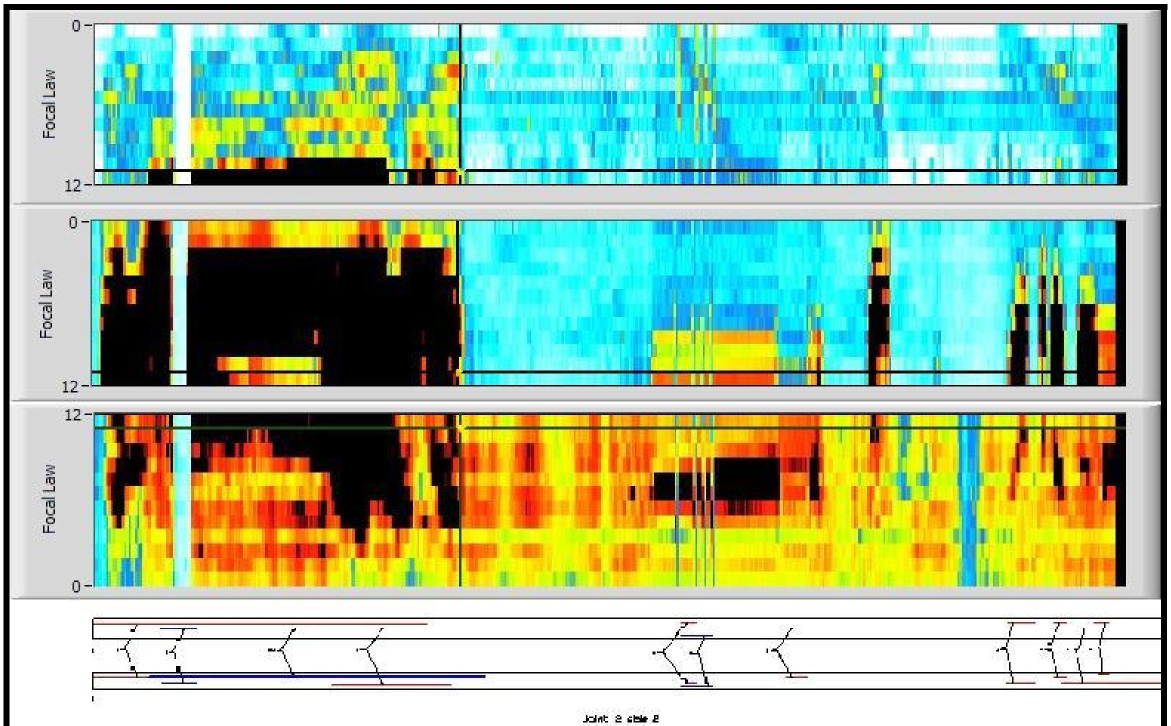
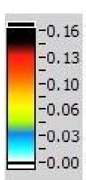


Figure 42 - Sample 2 Comparison of EMAT Response to Flaw Map – Low Gain





ID	Location	Length	Depth	Zone	Amplitude
1	0"	23 1/2"	5/8"	3	10+
2	16 3/4"	8 1/2"	13/16"	2	10+
3	41 1/2"	1"	3/4"	3	3
4	48 3/4"	1 1/2"	5/8" – 3/4"	2	5
5	64 1/2"	2"	11/16" – 3/4"	3	3
6	67 1/2"	1"	5/8" – 3/8"	3	3
7	68"	12"	3/4"	2	4
8	70 1/2"	1"	1/4"	3	2
9 *	4 3/4"	2 1/2"	3/4"	2	3
10 *	4"	23 1/2"	1/2" – 3/4"	2	10+
11 *	41 1/2"	2"	7/8"	1	10+

* These indications were detected from opposite side of weld. (opposite of EMAT)

Figure 43 – Sample 2 Comparison of EMAT Response to UT Flaw Map - High Gain

Laboratory Data Sheet — Northrop Grumman Newport News

Process
___ SMAW ___ GMAW X SAW | ___ Manual | X 1 ___ 3 ___ 5 X G | X Plate
___ GTAW ___ FCAW ___ OTHER | X Auto. | ___ 2 ___ 4 ___ 6 ___ F | ___ Pipe

Preheat (min): Ambient
Method: NA
Interpass (max): NA
Measured by: NA
Maximum interpass reached? ___ Yes X No

Equipment
Power Supply/Model: Miller CP/CC-1500
Torch/Gas Cup/Wire Feeder: Linde UEC-8
Current: ___ AC X DCEP ___ DCEN | ___ AC ___ DCEP ___ DCEN

Filler Material
A
Size/Brand/Type: 3/16" ESAB 40A MIL-EA1
PO/Heat/Lot:
Specification: MIL-E-23765/4
B

Tungsten
Type
Size
Other

Base Material
Type/Dimensions: Carbon Steel 1" x 20" x 31"
PO/Heat/Lot: NA
Specification: MIL-S-22698

Joint
Type B2V.2
Avg Bead Lgth 72"

Torch Angle
Lag 0^o
Tilt 0^o

Backside Prep/NDT
___ Ground ___ ___ Satisfactory
___ Gouged ___ ___ Unsatisfactory
Procedure ___ Initial ___

Visual Inspection
___ Ground ___ Satisfactory
___ As welded ___ Unsatisfactory
Procedure ___ Initial ___

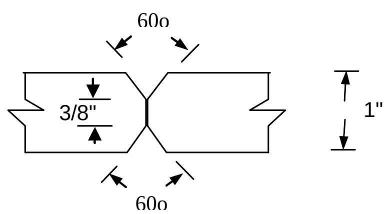
Shielding Method
Shielding Gas: NA
Top Flux: Lincoln 860
PO/Heat/Lo: NA

Final NDT
___ MT ___
___ PT ___
Procedure ___ Initial ___

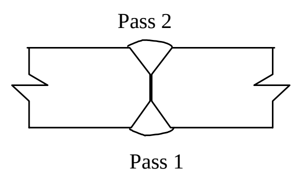
RT
X Accept ___ Reject
Radiograph to
Interpret to

UT
___ Accept ___ Reject
Ultrasonic to
Interpret to

Joint Sketch



Bead Placement



Pass No.	Current	Voltage	Filler Mat'l.	Electrode Stickout	Travel Speed (in/min)	WireFeed Speed (in/min)	Notes
1	825	35	A	1.5"	11		Bead looks good.
2	925	37	A	1.5"	10		Bead looks good.

Technician	Date	Joint No.
Harper, Tony	1/20/2004	All

Figure 44 – Typical Welding Technique