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JAN 1993

ULTRASONIC SENSING OF GMAW: LASER/EMAT DEFECT DETECTION SYSTEM

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EGG-M-92287

DE92 017916

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Abstract

In-process ultrasonic sensing of welding allows detection of weld defects in real time. A noncontacting ultrasonic system is being developed to operate in a production environment. The principal components are a pulsed laser for ultrasound generation and an electromagnetic acoustic transducer (EMAT) for ultrasound reception. A PC-based data acquisition system determines the quality of the weld on a pass-by-pass basis. The laser/EMAT system interrogates the area in the weld volume where defects are most likely to occur. This area of interest is identified by computer calculations on a pass-by-pass basis using weld planning information provided by the off-line programmer. The absence of a signal above the threshold level in the computer-calculated time interval indicates a disruption of the sound path by a defect. The ultrasonic sensor system then provides an input signal to the weld controller about the defect condition.

THE PURPOSE OF THE ULTRASONIC SENSOR is to detect defects in the solidified weld metal on a pass-by-pass basis (1-4) for a multipass, pulsed GMAW process. The sensor is being developed under the Programmable Automated Welding System (PAWS) project. The noncontacting sensor system (5) has two sensor components, an ultrasound generating source and an ultrasound detector, as well as a remotely located computer data acquisition and processing unit. The sensor will be demonstrated on thick section (31.8 to 41.3 mm, 1.25 to 1.625 in.) weld samples.

The ultrasound is generated by a short duration, 11 ns, light pulse from an Nd:YAG laser with an exit beam power of 56 mJ/pulse. The 1 mm laser spot is delivered at a 20 Hz rate to the solidified top surface of the weld several inches behind the electrode using focusing optics mounted on the laser head (6,7).

The ultrasonic detector is an EMAT and amplifier designed and fabricated for PAWS at the National Institute of Standards and Technology in Boulder, Colorado (8). The permanent magnet EMAT generates a magnetic field in the weld sample. The sound generated by the laser pulse interacts with the magnetic field, changing an associated electrical field. This interaction is detected by a pickup coil. The signal is then evaluated as an ultrasonic A scan.

The ultrasonic system includes the hardware and software necessary to monitor the condition of the solidified weld metal while receiving and sending information to a weld controller about the quality of the solidified weld bead.

SENSOR HARDWARE

Pulsed Laser Sound Generation. A first step in devising a noncontacting technique for sensing defect generation in the welding process is to develop a method for generating sound waves in the material. In this system, ultrasound is generated by a focused, 1 mm (0.039 in.) diameter laser spot from a pulsed Nd:YAG laser operating at 1064 nm. The short duration, 11 ns, laser pulse has a peak intensity of 10^7 W/cm² and generates high frequency, broadband ultrasound in the solidified weld metal by ablation. The sound waves arrive at the top surface of the weld sample, where they are received by the EMAT, after reflecting or mode converting at the bottom surface of the sample.

For the PAWS demonstration, the compact laser head is mounted on the weld head of a crawler. The laser head is 533 x 178 x 127 mm (21 x 7 x 5 in.) and 7.7 kg (17 lbs). The rugged laser head design provides optics sealed from the environment. To assure safe operation of the laser, the shutter and the high voltage supply are disabled by either computer or manual control. The laser head is connected to the laser power supply by an umbilical that supplies power and cooling to the laser head. A focusing optics fixture that houses a 50-50 beamsplitter, optional neutral density filters, and a 300 mm (11.8 in.) focusing lens is mounted in front of the laser to form the 1 mm (0.039 in.) spot size on the solidified weld bead.

EMAT Receiver. The basic components of an EMAT are a magnet, a conducting pickup coil, and amplifying electronics. The EMAT sensor assembly is 105 x 68.6 x 157 mm (4.13 x 2.70 x 6.18 in.). The height includes the cable to the associated electronics. The overall length increases to 163.5 mm (6.44 in.) with the addition of wheels to facilitate the movement of the EMAT down the weld sample. Figure 1 shows the EMAT assembly with the wheel carriage attached. In Figure 2 the laser and EMAT are shown mounted to the carriage of a sidebeam welder. In the demonstration system, the components will be mounted on the weld

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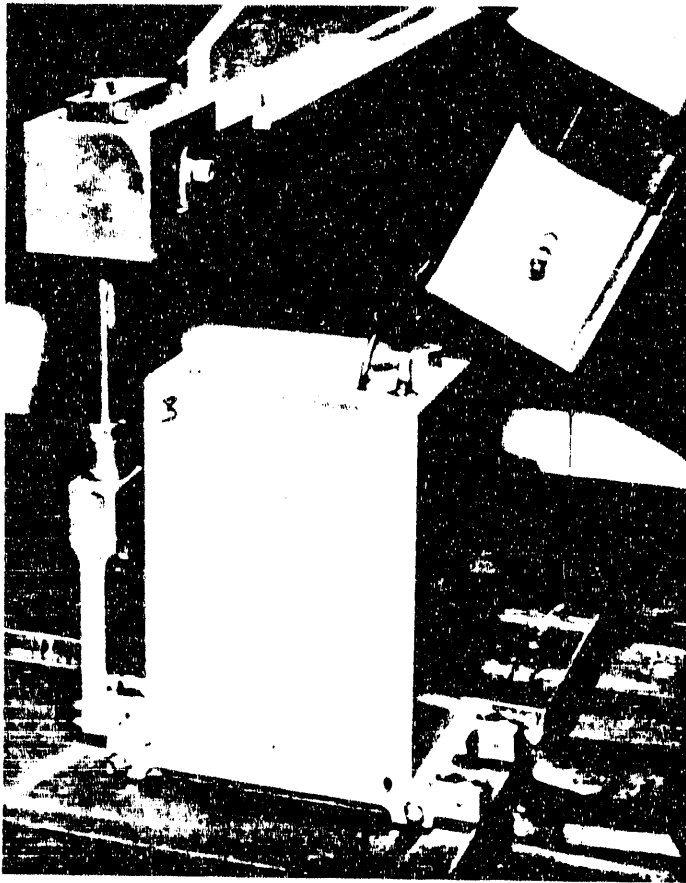


Fig. 1. EMAT assembly developed at the National Institute of Standards and Technology and pulsed Nd:YAG laser head with sealed optics



Fig. 2. Ultrasonic sensor components mounted on sidebeam welder

head of a crawler; the detection approach is the same for both fixings of the sensor components.

The EMAT produces a magnetic field in the sample using a neodymium-iron-boron permanent magnet. A magnetic pole-piece is placed between the permanent magnet and the pickup coil to intensify the magnetic field at the EMAT coil. The moving laser generated sound field causes the changes in the metal to move in the magnetic field, which generates a secondary field that is detected by a small pickup coil. The conducting pickup coil is a 25-turn, counter wound, center tapped, coil mounted behind a stainless steel plate. The entire unit is designed to be sensitive to incident shear waves arriving at 45° with a frequency range of 0.5 to 20 MHz. The EMAT is sensitive to a minimum flaw size of 1 mm (0.039 in.) in the plane of the ultrasonic wave perpendicular to the direction of weld travel.

Effective operation of the EMAT also requires amplification of the received signal; this is accomplished by a preamplifier and a main wound amplifier. The high gain, low noise preamplifier circuit will detect the circuit noise is located in the EMAT assembly that provide common mode rejection and signal amplification of approximately 90 dB. The main wound amplifier is located near the sensor computer away from the EMAT assembly and welder. This amplifier rejects electromagnetic interference picked up by the EMAT assembly and the 0.7 mV/22 nV signal amplifies the signal by 20 dB. After noise is added the signal bandwidth and outputs a signal to a 50 ohm load.

For the EMAT assembly to operate effectively on a weld sample, the pickup coil needs to be ~ 0.16 mm (6 mil) or less above the sample. To achieve this standoff distance and to allow the EMAT to move easily over the part being inspected, the EMAT is equipped with wheels. The wheels are electrically isolated from the weld sample using nonconducting shaft sleeves to avoid electrical interference from the welder. The EMAT assembly is attached to the crawler welding head by a mounting fixture; the weight of the EMAT is supported by weld sample. The path that the laser and the EMAT follow is dictated by the path of the crawler weld head; the sensor components are positioned at the start of the welding pass and not relocated during the pass. Thus, for the demonstration system, the sensor is used on linear welds with the EMAT and laser moving parallel to the weld centerline. With the addition of servo motors on the next generation of the ultrasonic sensor system, the EMAT and laser can inspect parts with other than linear paths.

Because the EMAT assembly is close to the preheated weld sample, external cooling is required to keep the magnet well below its Curie temperature and to cool the electronics enclosed in the EMAT assembly. The EMAT is currently designed to be placed on a plate preheated up to 93°C (200°F). Dry nitrogen or argon at 400 and 6.9 $\times 10^5$ Pa (25 ψ) and 10 psi is used as the cooling medium. The cooling line is attached to a 0.35 mm (0.02 in.) electrically insulated urethane located on the top of the EMAT assembly.

Computer System. The computer system for the ultrasonic

sensor acquires and processes information from the EMAT and determines if the weld is of acceptable quality. Information about unacceptable weld is sent to the weld controller. The central processing unit of the ultrasonic sensor is a full-featured 80486 based PC/AT compatible with a clock speed of 25 MHz. The CPU board has 4 megabytes of RAM memory, on chip memory cache, math co-processor, small computer systems interface and floppy controllers, and keyboard and VGA monitor ports. When the system is powered up, the watch-dog timer assures the successful start or restart of the system. The keyboard and monitor are necessary during the system integration and debugging phases. For the demonstration, the system operates without the keyboard or monitor.

A read-only solid state disk emulator and a read/write daughter board are used for storage of the operating system and data acquisition and processing software, and for temporary file storage of calibration and initialization values. The solid state disk emulator is equipped with an onboard PROM programmer. Utility software is available to copy files and programs on to the solid state disk emulator via a floppy disk.

A watch-dog timer/communication port card is used to reboot the sensor when the system crashes or hangs up due to an unexpected event. The watch-dog timer is equipped with a variable timer that is set by the sensor software. Before the end of each period the sensor software sets a bit in the register of the card. However, if the bit is not set before the end of the set period, the card provides an automatic low-going TTI signal that is used to reset the CPU using auto restart routines. A card is also provided on the receiver and transmit lines to protect the computer from high-level common mode voltage spikes.

An RS-422 interface is used to communicate with the controller. If unacceptable weld is detected, the ultrasonic sensor system computer streams data packets about this condition to the controller via the RS-422 interface. Throughout the welding operation, data packets are communicated over the interface between the sensor and the controller.

A waveform analyzer board analyzes the incoming EMAT signals. The board is externally triggered by a synchronization pulse from the laser. The board, operating in the peak detection mode, detects the presence of signals in two calculated time windows. The presence or absence of the signals in the selected time windows indicates the quality of the weld and the health of the sensor system.

The laser exit beam is controlled by the computer to ensure that the beam is only present when required for calibration and data acquisition. The signals to open the shutter and enable the high voltage creating the exit beam are sent to the laser from the digital I/O board. The status of the enable and disable of the beam on the digital I/O board is under the control of the ultrasonic sensor system's CPU. The CPU card, back plane, and necessary boards are housed in an industrial chassis in an environmental rack.

SENSOR SOFTWARE

Defect Detection Approach. Ultrasound data are acquired and processed by the ultrasonic sensor system to determine the quality of the weld pass. The presence of good quality weld results in two signals being detected by the system. One signal, referred to as the detection signal, indicates the quality of the weld. The second signal, referred to as the health signal, indicates the operational quality of the ultrasonic sensor system. In the presence

of a defect condition, such as incomplete penetration or porosity, the sound path of the detection signal is disrupted, resulting in a decrease in signal amplitude or complete loss of the signal. A confidence level evaluation is made by monitoring the amplitude of the health signal in a time window that is not likely to be altered by unacceptable weld quality. The health signal provides a means of determining that loss of the detection signal is due to a defect condition rather than to an equipment problem.

In the detection approach used for the ultrasonic sensor, there are three preparatory steps before acquiring data during a weld pass. The system completes acknowledgment and calibration sequences. Data describing the next weld pass geometry are then down loaded from the off-line programmer. These data are used by the ray tracing program in the initialization sequence to calculate the position of the laser and EMAT needed to direct sound through the critical fusion zone. Ray tracing also provides the arrival time and tangential displacement values of the signals of interest for monitoring the weld pass. These times are used by the computer to set the time gates on the waveform analyzer. The displacement values are used to determine the expected wave amplitude of arriving signals when no defects are present in the weld. The presence and amplitude of signals in two time gates are used to determine weld quality and confidence level.

Acknowledgment Sequence. The flow of data to and from the controller is initiated when the controller issues a request for the sensor system to check its system status. The sensor system responds with a status of acceptable or unacceptable. If the response is unacceptable, or if no response is received, the controller sets an error condition for the sensor system. The sensor remains in an off-line status for the welding pass, requiring sensor components to be placed in an idle position for that pass. Sensor components are positioned to avoid encountering physical obstacles, and the laser remains disabled for the entire welding pass. If the sensor status is acceptable, the calibration routine follows.

Calibration Sequence. Two positions on a calibration block are used for calibrating the system. The system interrogates weld of acceptable quality at Position 1 and of unacceptable quality due to incomplete penetration at Position 2. Communication between the controller and the sensor system directs and confirms sensor positioning on the calibration sample.

The sensor system performs the calibration at Position 1 to confirm that the system is operating correctly. The two predetermined calibration time windows are set on the waveform analyzer by the computer. These are time windows for the detection and health signals used to determine the weld quality and sensor operational status. For both the calibration and weld pass sequences, Window 1 is the defect detection window and Window 2 is the health of the system window. A third window is selected to determine the noise level. Based on the values in this noise window, the noise threshold is adjusted to the current level.

Once the values are set for both time windows, an amplification level is selected on the waveform analyzer board so that the voltage from an acceptable weld is just below saturation. A signal is sent by the sensor computer to the laser to open the shutter and enable the high voltage in the laser power supply unit. The computer verifies that the laser is enabled.

When the voltage level is set, the system acquires calibration data for Position 1, acceptable weld. The acquired signal is evaluated to ensure that both time windows have a signal of the expected amplitude, based on the prior calibration information. The amplitude of the received detection signal is recorded and the

confidence level is set. The noise level is also determined. A signal from the sensor system is sent to close the shutter and disable the high voltage when the signals are acceptable. If the signals are not acceptable, an error message is sent to the controller for manual intervention to check the sensor components.

When Position 1 is successfully calibrated, data are acquired at Position 2, the location of a known defect. (The timing windows, threshold level, and gain settings selected on the waveform analyzer board at Position 1 are unchanged for Position 2.) The acquired signals are evaluated to ensure that the detection signal on Window 1 is below threshold and the health signal on Window 2 is acceptable. Once this determination is made, the laser beam is disabled. The calibration values are sent to a disk file for use in the event of a reboot of the system.

Initialization Sequence. After calibration the sensor system is ready to receive information from the controller about the next welding pass. The ultrasonic system alerts the controller that calibration is complete. The controller computer then sends the sensor system the data packets required for the ray tracing program to calculate the location of the EMAT coil center and laser spot for the next weld pass. The packets passed to the sensor by the controller for initialization fall into three areas. The first packet sends information about the joint type. The joint types are established in advance, so only an integer value is passed to indicate to the sensor which joint type is being evaluated. The second packet provides the fill strategy to be followed and the weld pass number of the next pass. The final packet gives information from the off-line programmer about the next weld pass geometry in the form of twenty coordinate pairs for positions at selected intervals over a cross section of the weld pass.

Using the packet values, the region for inspection is established. It is the area where the next weld pass intersects the sidewall or the adjacent bead of the pass being covered. This establishes one point through which the sound must pass. The other points that are known to the system are the coordinate pairs on the next weld pass. These points are potential laser spot locations. The ray trace program iterates over these points with rays that pass through the region of interest. Only rays that require a single reflection or mode conversion to reach the EMAT are considered. These ray paths are referred to as two-leg paths. The two-leg paths are evaluated to determine if they reach the top surface of the weld sample at an acceptable distance from the top edge of the weld preparation (≥ 12 mm, 0.47 in.) and do not travel a metal path that exceeds four times the part thickness. A two-leg ray that meets these requirements is a candidate ray for the detection signal. The candidate ray with the greatest tangential velocity component is selected as the detection ray. The initialization values of signal arrival time, tangential displacement, and waveform analyzer board settings for the health, detection, and noise signal are written to disk for use if the system is rebooted.

If the initialization routine does not establish an acceptable ray for defect detection for the next weld pass, the controller is sent an appropriate error code. The EMAT is designed to accept the tangential velocity component of shear waves, so it is not sensitive to ray paths ending in longitudinal rays. On some lower passes, only ray paths ending with a longitudinal ray reach the EMAT, so the sensor system is set off-line for those welding passes.

Weld Pass Defect Detection Sequence. Once the initialization sequence determines the optimum locations for the laser and EMAT and the waveform analyzer is readied, the sensor system is

prepared to monitor the welding pass. The ultrasonic sensor alerts the controller that initialization is complete and the sensor components can be moved to the weld start location. The controller moves the sensor components to the starting location for the welding pass and alerts the sensor system when the sensor components are correctly positioned for data acquisition. The controller sends a message to indicate that the EMAT is at the weld start position, and another message when the weld reaches the normal termination position. When the ultrasonic system has monitored an entire welding sequence for filling the joint, the controller must send the ultrasonic sensor an off-line command to clear the stored values in the disk calibration and initialization files prior to starting a new joint.

A command can also be issued by the controller when the welding process is interrupted during a weld pass, e.g., to change a consumable material during a weld pass. When the controller issues an emergency stop command, the sensor system disables the laser during the emergency stop period. When welding is to resume, the controller sends a message to the sensor that welding is to start, and the sensor computer enables the laser beam.

The sensor system sends the controller a data packet only when a defect is detected. Defect conditions are evident when the detection signal is below threshold in Window 1 and the health signal is present in Window 2. The defect data packet provides information on the defect type and confidence level of the defect call. Currently, the ultrasonic sensor provides the controller with information on a defect condition four times per second (4 Hz).

The sensor system can store the voltage of the detection signal for system debugging. This information can be plotted against distance along the weld centerline. Distance information is approximated using the expected travel speed; therefore, distance values can vary by up to 12.7 mm (0.5 in.). Figure 3 shows such a plot for the fourth weld pass on a 31.8 mm (1.25 in.) V-groove weld sample. The area of interest for detecting defects is the sidewall between passes three and four.

Based on the results of the calibration and initialization sequences, the threshold for acceptable weld is placed at 1.2 V. Therefore, all voltage values above 1.2 indicate acceptable weld. The system threshold can be adjusted to increase or decrease sensitivity depending on the requirements of the welding application. Three consecutive signals are required for the sensor to call an area acceptable or unacceptable; this avoids defect calls resulting from minor surface variations or transient fluctuations in the laser power.

The sample was radiographed to confirm the location of incomplete sidewall penetration for sensor system validation. From the radiograph, areas of continuous incomplete penetration are located between 178 and 279 mm (7.0-11.0 in.) and at 318 mm (12.5 in.). The ultrasonic system identified incomplete penetration in these areas as signal voltages are below the 1.2 V threshold (see Figure 3). The sensor system detected other areas of intermittent incomplete penetration that were confirmed by the radiograph. Mild incomplete penetration is present in the first 381 mm (15 in.) of weld. The only area of good weld is from 381 mm (15 in.) to the end of the distance monitored. The sensor system's ability to detect incomplete penetration was validated for other selected passes using the procedures described above. Those tests confirmed the system's ability to detect incomplete penetration under GMAW conditions with travel speeds varying from 178 to 227 mm/min (4-9 in./min).

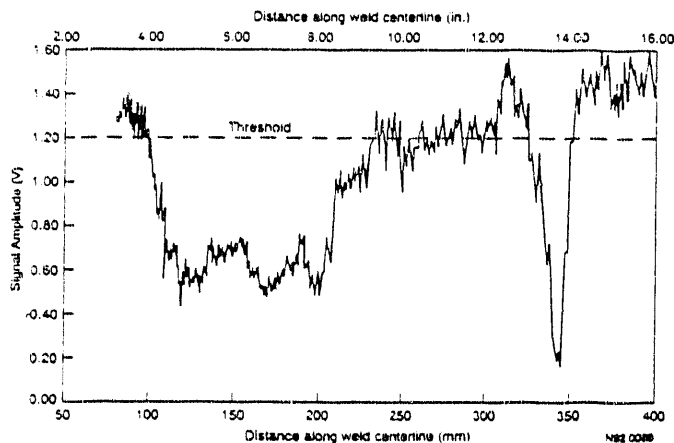


Fig. 3. Distance vs. voltage for fourth weld pass.

CONCLUSION

An ultrasonic sensor system can be used to detect defects on a pass-by-pass basis when joining thick section plate using pulsed GMAW. The system is noncontacting and presents no weld contamination problems. The present system can detect defects in linear sections of weld on plate preheated to 93°C (200°F) using a pulsed laser to generate ultrasound and an EMAT to receive the ultrasound. A PC-based computer system controls data acquisition and processing. When a defect condition is detected, the sensor computer alerts the controller that weld of unacceptable quality is being made. The sensor system provides the controller with input at 4 Hz about defect conditions. The defect information provides input for feed-back control of the GMAW process.

ACKNOWLEDGEMENT

The technical assistance of U.S. Wallace, J.E. Lee, J.G. Rodriguez, and N.G. Boyce is acknowledged. Appreciation is expressed to C. Null, Naval Sea Systems Command, R. Morris and D. Rome, Carderock Division, Naval Surface Warfare Center, for their support. This work is supported by the U.S. Navy under DOE Idaho Field Office Contract DE-AC07-76ID01570.

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