AUTOMATED SYSTEM FOR LASER ULTRASONIC SENSING OF WELD PENETRATION

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Abstract—An on-line sensor is required for real-time control of penetration depth in robotic welding. Currently, no on-line techniques exist for direct penetration depth measurement. The development of a penetration control system will significantly reduce the costs associated with repairing or scrapping defective welds. Laser array generated ultrasound is a noncontact, nondestructive method that can potentially be used to measure weld penetration. This paper will discuss the design and implementation of an automated system that was used to measure the depth of simulated solidified welds. The system consists of a laser array generation source and an electromagnetic acoustic transducer (EMAT) receiver. Measured penetration results for the simulated weld are compared with the exact results. Experimental results will also be shown for array gain measurements in order to demonstrate the power of the array. This automated system is being modified in readiness for use in actual robotic welding. © 1997 Elsevier Science Ltd

1. INTRODUCTION

This paper will present steps taken to develop an automated laser ultrasonic array testing system for weld penetration measurements. This system was calibrated by using it to measure various depths in steel blocks. These slotted blocks were heated to as high as 95°C during the measurements. Each of these blocks was used to simulate different levels of penetration after the butt welding process. Some of these calibration results will be presented to demonstrate the accuracy of the system. Since a laser array technique was used as a means to generate the ultrasound, some array results will be presented to show how the array enhances ultrasonic signals.

The automated measurement system was built to measure penetration depth during simulated welding. The authors chose to use simulated welds rather than actual welds because it is less expensive, and easier to test and optimize the system during simulated welding than during the actual robotic welding. Once the system is optimized during the simulated welding, it can then be enhanced for use in the real welding process, which is
what the authors are currently doing. On the other hand, if the system did not work during the simulated welding process, it could easily be scrapped without any big financial loss.

The level of welding automation has been extended through the use of robots. Robots are able to weld with greater speed, higher quality, and better reproducibility than human operators. Robots have no inherent intelligence, unlike human operators, and their performance cannot be evaluated until the process is completed and off-line testing can be performed. When defects are detected off-line, costly repairs must be made which may also reduce the quality of the weld. The detection and removal of these defects through on-line sensing will both improve weld quality and reduce costs through the elimination of post-weld repair and through increased processing speed. The major obstacle to fully automated robotic welding has been the lack of reliable noncontact, nondestructive on-line sensors with the ability to detect defects as they form and with the capability of operating at high temperatures and in harsh environments. The work reported here is a stepping stone towards overcoming these obstacles.

2. STATE OF CURRENT RESEARCH

Most ultrasonic weld inspection systems to date have been post-process and contact in nature [1, 2]. While apparently successful, this type of ultrasonic inspection is subject to a wide range of variables and difficulties [3]. Fenn demonstrated early success in controlling weld pool penetration with direct measurement by using piezoelectric transducers (PZTs) on either side of the weld pool [4]. One PZT generated a shear vertical wave (SV), while the other received the transmitted wave. This system was able to transmit ultrasound through temperature gradients approaching 1000 °C/mm. The applicability of the technique was limited due to the need to couple PZTs to the surface of the test piece with couplant.

Researchers at EG&G Idaho demonstrated the use of contact pulse–echo ultrasonics for weld geometry determination [5–7]. Again, the major difficulties included contact transducers and difficulties in signal interpretation. To eliminate the need for contact transducers to generate ultrasound, lasers were investigated as a non-contact source as early as 1963 by White [8]. In 1982, Scruby investigated laser generated ultrasound in metals [9]. In 1988, Aussel investigated both thermoelastic and ablative laser generation [10]. In 1987, Jarzynski and Berthelot used fiber optics for spatial and temporal control for beamsteering [11]. In 1989, Ing used a Bragg cell for beam steering of laser ultrasound and in 1991 investigated ultrasonic directivity patterns of a moving source [12, 13].

For weld penetration control, the EG&G group began to investigate ultrasound generation by pulsed Nd:Yag laser and reception by an electromagnetic acoustic transducer (EMAT) [14]. This solved the problem of requiring mechanical contact of the source and receiver with the test piece, but the low sensitivity of the EMAT required a very strong ultrasound source. This required that the ultrasound be generated in the ablation regime by Q-switching the laser. The ablation threshold is above approximately 20 MW/cm², given by Scruby [15]. Q-switching a laser causes a significant increase in peak power, with a reduction in pulse width to less than 15 ns. This created a new set of problems. Ablation causes surface damage, making the system destructive rather than non-destructive.

Beginning in 1990, Ume and his graduate students investigated directional laser generation of ultrasound with optical fiber arrays [16–24]. Using principles of constructive wave interference, optical fiber arrays can generate stronger ultrasound than single laser
source schemes without causing ablation. Currently, laser-fiber bundle line source arrays are under investigation in conjunction with time of flight techniques [25–27].

3. MEASUREMENT ISSUES

Received laser generated ultrasound signals may be processed in several ways. The measurements typically made are time of flight and amplitude. With the automated system described in this paper, the complete digitized ultrasound signal may be placed in permanent storage where the time of flight and amplitude may be determined with a high degree of accuracy.

The directivity of an ultrasound source is the variation of the amplitude of the generated ultrasonic wave with respect to its angle measured from the surface normal. Knowledge of the directivity of a source is very important because the directivity information is involved in the design of all ultrasonic systems. The procedure for the measurement of an ultrasonic directivity pattern requires moving the receiving transducer manually around a steel semi-cylinder while recording the ultrasound amplitude at the correct time-of-flight. For accurate results, the power of the laser light must be held constant for each measurement in a data set. The design of the system provides for consistent ultrasound amplitude measurements.

For the measurement of simulated solidified weld penetration depth, the time-of-flight of the received ultrasound is used since they are directly related. The procedure involves performing ultrasound time of flight measurements at different weld penetration depths.

4. HARDWARE CAPABILITIES

The experiment apparatus used in the measurement of penetration depth is described in Table 1.

5. DATA ACQUISITION PROCEDURES

An automated system for the acquisition of laser generated ultrasound and subsequent measurement of material parameters requires the oscilloscope, laser, and PC to operate synchronously. The distal end of the fibers is first positioned near the surface of the material on which ultrasound is to be generated. After the fibers are in position, the laser pulsing begins. The laser has an internal clock with a rate of 10 Hz which is used both to control the pulse rate and to trigger the oscilloscope. Laser light is transmitted to the material surface by the fiber optic array where ultrasound is generated. The generated ultrasound travels through the material until it is received by the transducer (EMAT or PZT). After filtering and amplification, the transducer signal is delivered to the oscilloscope which has already been triggered by the laser clock. A total of 256 signals are collected and averaged by the oscilloscope in this manner. For diffracted ultrasound measurements, the signal-to-noise ratio after averaging ranged from 6 to 12 dB. Because the laser pulses at a rate of 10 Hz, the total time required to acquire one averaged waveform is 25.6. This time can be reduced to 2.56 s by using a laser with 100 Hz repetition rate, and averaging less than 256
Table 1.

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Manufacturer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Continuum</td>
<td>Shurelile II: Nd:YAG, Q-switched, 5–7 ns pulsewidth, 10 pulses per second, 650 mJ/pulse, 6 mm beam diameter</td>
</tr>
<tr>
<td>Attenuator</td>
<td>CVI Laser</td>
<td>Custom variable attenuator</td>
</tr>
<tr>
<td>Fiber</td>
<td>CeramOptec</td>
<td>1 mm core hard clad silica</td>
</tr>
<tr>
<td>Positioner</td>
<td>Line Tool</td>
<td>XYZ micrometer positioner</td>
</tr>
<tr>
<td>Samples</td>
<td>Custom</td>
<td>1020 steel, 25.4 mm thick, 254 mm wide, 254 mm long, plates. Four with 1 mm thick and 6.35, 9.525, 12.7, or 15.875 mm deep machined grooves, respectively</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Panametrics</td>
<td>Videoscan 3.5 and 5 MHz, 3.175 and 12.7 mm diameter, longitudinal</td>
</tr>
<tr>
<td>EMAT</td>
<td>Industrial Sensors</td>
<td>Custom electromagnetic acoustic transducer with integrated permanent magnet and pre-amp. 7 MHz bandwidth. Sensitive to out-of-plane displacements</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>Tektronix</td>
<td>2430A digital storage oscilloscope, 100 MHz bandwidth</td>
</tr>
<tr>
<td>Filter-Amplifier</td>
<td>Krohn-Hite</td>
<td>Custom variable band-pass filter-amplifier set for 36 dB gain set for Butterworth bandpass filtering from 0.5 to 5 MHz</td>
</tr>
<tr>
<td>Receiver</td>
<td>Metrotek</td>
<td>MR101A, up to 63 dB gain, high-pass filtering above with adjustable cutoff of 0.5 to 4 MHz</td>
</tr>
<tr>
<td>Power Meter</td>
<td>Scientech</td>
<td>MC 2501 thermal laser power meter</td>
</tr>
<tr>
<td>Micro-Computer</td>
<td>IBM</td>
<td>386 processor with 25 MHz clock. Data acquisition and analysis is performed with LabWindows and Matlab software. LabWindows drivers are used in programs written to download waveforms from the scope through the GPIB port. Matlab software is used to display and analyze the waveforms. The Matlab programs written by the authors to perform the data acquisition is called r/.m.</td>
</tr>
</tbody>
</table>

.signals. If 32 samples are averaged (see Fig. 5) when a 100 Hz laser is used, the total time to acquire one waveform will be 0.32 s.

To obtain useful information from the averaged ultrasound waveform, it must be processed on the PC. The program previously described, r/.m, is used to download the data from the oscilloscope for storage and further processing. For the weld penetration measurement, the time of flight of the ultrasound would first be calculated from the raw ultrasound data, and from that information penetration depth would be calculated. The program may be customized to fit the application giving the system complete flexibility.

The precision of the measurements made on the oscilloscope are ±5 μV for voltage and ±5 ns for tie. It was determined through 10 repeated weld penetration depth measurements that the precision of the time measurement on the oscilloscope determines the overall system precision. The overall system accuracy depends on the application; for weld penetration depth measurement, the error is 0.5 mm or 3.125%.

When the system described here is implemented in the real robotic welding process, fused silica fibers will be used. Fused silica fiber can withstand high temperatures (more than 1000°C). The ends of the fibers will be enclosed inside a small scale insulating box with a lens at the end (bottom) of it. This will shield the fibers from excessive heat and welding particles.
5.1. Array gain measurement

Figure 1 shows the experimental setup for array gain measurement of ultrasound generated by laser light from a line array-optical fiber bundle. After passing through the variable attenuator, the laser beam was incident onto the proximal end of a bundle of up to seven optical fibers each 2 m long. The desired light intensity in the fibers was achieved by positioning the proximal end of the fiber in the center of the laser beam while adjusting the variable attenuator. During this optimization, light energy from the distal end of each fiber was measured by the power meter to produce a peak power of 20 MW/cm². The Q-switch signal from the laser was used to trigger the oscilloscope. The fibers were arranged in a line at their distal end. The light traveling in the fibers left the distal end of the fiber just above the sample in the center of the flat side. The spot size was only slightly larger than 1 mm for each fiber. The light was then absorbed at the sample surface creating a thermoelastic expansion which is the source of the ultrasonic waves in the bulk of the sample.

To measure the array gain, a piezoelectric transducer (PZT) was used. The PZT was positioned on the center of the curved side at an angle of 70° from the axis of the PZT and was coupled to the sample surface with a viscous liquid couplant. The PZT was allowed to receive 256 waves for averaging by the oscilloscope. The signal from the PZT was filtered and amplified by the MR101 receiver. The averaged signal from the receiver was then displayed on the oscilloscope and stored. The MATLAB program then called for the signal from the oscilloscope. The stored waveform was then transmitted digitally from the oscilloscope to the PC through a general purpose interface bus (GPIB). Once stored in the PC, the program (rl.m) then determined amplitude.

Fig. 1. Experimental setup for array gain measurement.
The waveforms shown were longitudinal waves measured at 70°. Equation (1) describes the theoretical variation of normalized ultrasound amplitude \( A_N \) with number of fibers in the bundle \( N \). Normalized amplitude is obtained by dividing each measured amplitude by the amplitude measured when one fiber is in the bundle.

\[ A_N = N. \]  

Figure 2 shows the measured variation in amplitude for increasing numbers of fibers in the line array compared with the theoretical variation. The experimental measurements agree well with the theoretical predictions.

5.2. Penetration depth measurement

Figure 3 shows the experimental setup used for the measurement of penetration depth in simulated solidified welds with diffracted ultrasound and EMAT receiver. Ultrasound was

![Diagram](image-url)

Fig. 2. Normalized ultrasound amplitude vs number of fibers in bundle.

![Diagram](image-url)

Fig. 3. Experimental setup for penetration depth measurement in simulated solidified welds.
generated by the seven fiber array on 1020 steel plates 25.4 mm thick, from room temperature to 95°C. The unwelded portion of the plate was simulated by machined grooves corresponding to penetration depths of 6.35, 9.525, 12.7 and 15.875 mm, respectively. At this time, the authors are not concerned with base materials consisting of sandwich structures of absorbing layers between assembled parts. Therefore, the resonance problem of the metal will not be an issue.

In this configuration, the time of flight of the diffracted ultrasound is dependent on the penetration depth. As the penetration depth increases, the path length of the waves which are directly diffracted increases due to the placement of the array and receiver on the same side as the weld. The relationships are given in eqns (2) and (3) for incident shear waves and diffracted shear waves. These relationships are derived from geometrical relationships.

\[ t = \frac{2\sqrt{s^2 + PD^2}}{c_s(T)} \]  
\[ PD = \sqrt{\left(\frac{t \cdot c_s(T)}{2}\right)^2 - s^2}. \]

In these relations, \( t \) is the time of flight, \( s \) is the distance from the groove to the EMAT and line array of fibers, \( a \) is the plate thickness, \( PD \) is the penetration depth, and \( c_s(T) \) is the shear wave speed as a function of temperature \( T \).

To determine the effect of elevated temperatures on the ultrasound diffraction process, the plates were heated with a strip heat which was C-clamped to the bottom of the plate parallel to the weld axis. The temperature was identified by the temperature at \( s = 0 \) mm. The temperature profile in the plate is shown in Fig. 4.

The laser was pulsed at a rate of 10 Hz. The laser beam was attenuated by the variable attenuator and then fell incident on the end of the seven fiber bundle. The light falling on the ends of the fibers was transmitted to the workpiece. At the workpiece the array of fibers was arranged in a line parallel to the axis of the weld at a distance \( s = 4 \) mm. A line of source of ultrasound was generated in the plates. The waves incident on the tip of the groove were diffracted. The diffracted ultrasound was received by the EMAT. The EMAT coil was located symmetric to the array at \( s = 4 \) mm.

![Fig. 4. Temperature profile of plate while measuring diffracted ultrasound with EMAT.](image-url)
The signals from the EMAT were filtered and amplified with a gain of 36 dB and bandpass filtering from 0.5–5 MHz. Signals from the filter were averaged on the oscilloscope 256 times, stored, and downloaded to the PC through a GPIB bus. Figure 5 shows the effects of averaging the signals with an increasing number of samples. Even though 256 samples were averaged, averaging 32 samples would have sufficed. Time of flight measurements were made on the PC using MATLAB software. The error in the time of flight measurements was determined through 10 repeated measurements to be 5 ns which was the precision of the oscilloscope when the time scale was 1 or 2 μ/division.

5.3. Discussion of the results

Figure 6 shows the received ultrasound for various penetration depths at \( T = 95^\circ C \). The first waves, shaded lightly, were the directly diffracted shear waves. The second waves, shaded darkly, resulted from shear waves incident on the groove, mode converted into Rayleigh waves traveling down the groove and reflected from the bottom of the plate, and then Rayleigh waves diffracted back into shear waves.

Figure 7 shows the penetration depth as a function of time of flight of the incident and diffracted shear waves. In comparison with the theoretical results, the received waves arrived later than, or were offset with respect to, the theoretical predictions. This is due to the delay induced by the processing electronics and due to the delay in triggering the oscilloscope.

![Fig. 5. Signals measured with increasing number of samples averaged.](image-url)
Fig. 6. Diffracted ultrasound received by EMAT at 95°C.

Fig. 7. Penetration depth vs time of flight for incident and diffracted shear waves.
from the laser's Q-switch signal. The average offset of the experimental measurements may be calculated and removed from the raw data. If the average offset is subtracted from the raw data, the experimental result agrees well with the theoretical predictions. For the incident and diffracted shear waves after the offset is removed, the maximum observed error was 0.5 mm or 3.125%.

The experimental measurements of penetration depth with diffracted ultrasound received by an EMAT receiver agreed well with theoretical predictions. The penetration depth increased with increasing time of flight. The largest errors in measured penetration depth observed were 0.5 mm. If the signal received by the EMAT shows signs of deterioration, the signal strength can be increased by: (1) using bigger diameter fibers and/or increasing the number of the fibers in the array, and (2) increasing the sensitivity of the EMAT. It is also important to note that the time of flight is what is being measured and not the amplitude.

6. CONCLUSION

The system described provides an accurate and repeatable method of measuring ultrasound directivity and penetration depth in simulated solidified welds. The system is also being used to measure penetration depth in a simulated liquid weld pool. The measurement of penetration depth in simulated solidified welds has demonstrated the feasibility of applying this technique to the on-line measurement of weld penetration in the solidified weld region. The proof-of-principle is now being demonstrated in the actual welding process.

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REFERENCES


