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Direct Measurement of Solids: High Temperature Sensing

Final Report

**Experimental Development and Testing of
High Temperature Pulsed EMATs**

**D. M. Boyd
G. E. Spanner
P. D. Sperline**

April 1988

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
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EXECUTIVE SUMMARY

BACKGROUND

Pacific Northwest Laboratory (PNL) has worked with the Department of Energy's (DOE) Office of Industrial Programs (OIP) and the steel industry through the American Iron and Steel Institute (AISI) for the past few years to identify areas that would be of greatest benefit to the steel industry. This program was initiated in 1983 at PNL as a cooperative effort between OIP and AISI to address the specific area of determining internal temperatures in hot steel bodies. The AISI has contributed funding and valuable in-kind services throughout the program.

The program was completed with the demonstration of a pulsed laser transmitter and pulsed EMAT receiver on hot steel samples. Preliminary testing of an EM pulser transmitter and pulsed EMAT receiver was also performed. The time-of-flight measurement system was demonstrated in the laboratory and proved the concepts for momentary contact for acoustic velocity measurement.

This final report describes work carried out on the "Direct Measurement of Solids: High Temperature Sensing" project at PNL. The program is working toward the development of a non-contacting sensor system for measuring the internal temperature of hot steel objects. Such a system would be of value to the steel industry because it would lead to reduced energy costs, increased productivity, and improved quality control at steel mills [1].

OBJECTIVES

In building on prior work performed during the term of this program, the current objective is to demonstrate an ultrasonic velocity measurement system that is capable of operating on steel samples at temperatures as high as 1100°C (2021°F). In support of this objective, three sub-objectives were identified. First was to demonstrate a pulsed laser source of ultrasound in steel, second was to develop a high-temperature electromagnetic acoustic transducer (EMAT) receiver, and the third was to assemble a testing laboratory for the development of the high-temperature measurement system. Late in the project a fourth objective was identified, development of a high temperature electromagnetic (EM) pulser as an ultrasonic transmitter.

TECHNOLOGY TRANSFER

Technology transfer is a significant portion of this project. Toward that end, representatives of the steel industry participated directly in the research and in technical guidance of the project. They also provided some of the test samples and supporting metallurgical data.

ACCOMPLISHMENTS IN PHASE II FOR FY85

The Phase II work begun in FY84 with the purchase of high-temperature shear and longitudinal EMATs was continued into FY85 [2]. Three test blocks were fabricated and heated to temperatures as high as 800°C and tested using the EMATs.

The shear-wave EMAT provided strong signals from room temperature up to the Curie temperature when the steel becomes nonmagnetic. The longitudinal-wave EMAT gave detectable signals only in a narrow temperature range where the surface layer was just below the Curie temperature and the interior was non-magnetic. The work demonstrated that it is possible to obtain time-of-flight measurements on hot steel at temperatures that are typical of many production conditions.

ACCOMPLISHMENTS IN PHASE III FOR FY86 AND FY87

The system being developed uses a pulsed laser to generate ultrasound pulses in steel objects and an electromagnetic acoustic transducer (EMAT) to receive them. After digitizing the EMAT response from the laser-generated ultrasonic pulse, a measurement of the time of flight of the pulse is taken. The time of flight is then combined with the object's length to calculate the ultrasonic velocity at the object's temperature. Because a known relationship exists between ultrasonic velocity and steel temperature, the temperature can then be calculated from the velocity. During the final quarter of the program, the addition of a high-temperature EM pulser evaluation was performed.

A system for making time-of-flight measurements on hot steel objects (intermittently up to 1400°C) has been set up in the laboratory. Key components in the system include a pulsed laser, minicomputer, digital oscilloscope, pulsed electromagnet EMAT, and EM pulser. Much of the EMAT development is being done by a subcontractor who has experience with high-temperature EMATs. The goal for the system is that it be capable of operating continuously on steel at 1300°C. The following tasks were completed during this phase of the project:

- The high-temperature testing laboratory was assembled and used for all laser and EMAT development.
- Three prototype high-temperature pulsed EMAT receivers were designed and assembled. Experiments have been carried out with the system at internal steel temperatures above 1300°C using the pulsed laser as the acoustic transmitter and the pulsed EMAT as the receiver. Both stainless steel and carbon steel samples were tested using the high-temperature EMAT.
- An electromagnet (EM) pulser to replace the laser was also designed and assembled by the subcontractor. High-temperature testing results of the evaluation of the EM pulser and pulsed EMAT receiver were performed on a 304L stainless steel sample to 1100°C.

RECOMMENDATIONS

- Demonstration of the high-temperature EM pulser and pulsed EMAT receiver should be tested in a field environment. Through a cost-sharing program between DOE/OIP, AISI, PNL, and Magnasonics, this work will be performed in early CY 1988.

- Development and integration of a high-temperature thickness measurement technique with the EM pulser/EMAT receiver should be performed. This task will allow for the continued technology transfer of the ultimate objective of achieving internal temperature measurement using ultrasonic velocity.
- Steel plant applications and potential technology transfer of work performed at PNL and NBS would help to direct the required developments in high-temperature sensing.
- Along the lines of more fundamental research is the required investigation of the attenuation and texture effects of acoustic transmission at high temperatures. Work in this area would allow for further refinement to the EMAT sensitivity and the investigation of lower frequency (500 to 750 kHz) pulsed EMAT designs.

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The technology transfer aspects of this project between the Department of Energy and the American Iron and Steel Institute (AISI) have also identified several people who have supported this program. We would like to acknowledge the guidance received from Dr. James R. Cook of the AISI committee. Additional thanks go to Dr. Bernard Droney for his technical insight and hands-on support to this project.

1.0 INTRODUCTION

This report describes work carried out as part of the "Direct Measurement of Solids: High Temperature Sensing" project that is sponsored primarily by the Department of Energy's Office of Industrial Programs. Secondary sponsorship and technical guidance are provided to the project by Task Group 5-4 of the American Iron and Steel Institute (AISI). This report covers the time period from October 1985 through December 1987.

1.1 PURPOSE AND OBJECTIVES

The long-term objective for the project is to develop a non-contacting means for determining the internal temperature profile of hot steel objects. Successful development of this technology will be beneficial to the steel industry because it can lead to significant energy savings and productivity improvements.

The specific objective of the work reported herein is to develop and demonstrate a non-contacting sensor for measuring ultrasonic time of flight in steel objects at temperatures up to 1300°C. This objective supports the long-term objective because ultrasonic velocity is known to vary inversely with steel temperature. By measuring the ultrasonic time of flight through a known metal distance, the velocity can be calculated, and from the velocity can be drawn conclusions regarding internal temperature of a steel object.

The technical approach selected to meet these objectives is to use a pulsed laser as an ultrasound transmitter and an electromagnetic acoustic transducer (EMAT) as a receiver. A longitudinal-wave ultrasonic pulse is caused to travel through a steel object by striking the object with a very short laser pulse at high enough energy to cause slight ablation [3,4,5]. The acoustic wave then travels to the far side of the object where it is detected by the EMAT. The time elapsed between pulsing the laser and detecting the ultrasound pulse at the EMAT is the time of flight for the pulse through the object.

EMATs were selected for the ultrasound receiver because they do not require physical contact with the test piece, which makes them adaptable to high-temperature operation. References on EMAT operation are available in many publications [3,4,5]. In order to obtain optimum efficiency of the EMAT, contact with the surface is required; however, no acoustic coupling liquid is required. In an EMAT receiver, a magnetic field is set up just below the surface of the test piece by either an electromagnet or a permanent magnet. When an acoustic pulse enters this magnetic field region, it causes the particles of the test piece to vibrate. The vibrations in the presence of the magnetic field cause eddy currents to flow in the test piece. These currents in turn induce opposing currents to flow in the EMAT's coil. It is these induced currents in the EMAT coil that are amplified and detected when the ultrasound pulse is received.

The following objectives were established for this work:

1. Set up and test a laser subsystem to generate ultrasonic pulses in the steel samples.

2. Develop and evaluate a high-temperature EMAT receiver subsystem.
3. Integrate and evaluate the laser/EMAT system on furnace-heated steel blocks.
4. Develop and evaluate a high-temperature EM pulser transmitter.

1.2 HISTORICAL SUMMARY

This project was begun at PNL during FY 1984 with an analysis of possible approaches to internal temperature measurement of hot steel objects. The analysis indicated that ultrasonic time-of-flight measurements, combined with other information, could be used to determine the internal temperature profile of steel objects. Limited experiments were also carried out at slightly elevated temperatures to demonstrate that the technical approach was feasible.

During FY 1985, experimental work was begun in earnest with EMATs used as transmitters and receivers of ultrasound. Surface temperatures approaching 900°C were encountered during the experiments. The following conclusions and recommendations resulted from the FY 1985 work:

- Ultrasonic velocity measurements could be used to calculate the average internal temperatures of steel objects.
- Due to metallurgical factors, neither longitudinal- nor shear-wave EMATs are capable of generating ultrasonic pulses in all steels of interest throughout the temperature range of interest. It was therefore recommended that a pulsed laser be used for generating ultrasonic pulses in future work.
- An EMAT for receiving ultrasound should be developed that would withstand surface temperatures as high as 1300°C. Recent work using a laser/EMAT system has been demonstrated as a viable technique for high-temperature measurements [3].
- Longitudinal waves should be used in future work because they are not as severely attenuated at high temperatures as shear waves. Further details concerning prior work on this project can be found in two reports published by PNL: "Direct Measurements of Solids: High Temperature Sensing, Phase I, Analytical and Experimental Evaluation" (PNL-5037) and "Direct Measurements of Solids: High Temperature Sensing, Phase II, Experimental Development and Testing on Furnace-Heated Steel Blocks" (PNL-5725).

1.3 TECHNOLOGY TRANSFER

The underlying reason for executing this research project is to develop a sensor system that can and will eventually be deployed in the steel industry. Therefore, technology transfer is an essential part of this research so that the sensor developed will be applied in the industry. In carrying out this research, technology is being shared among PNL, the steel industry, the EMAT

vendor, and the National Bureau of Standards. Each of their roles is described below.

- Steel Industry - Through Task Unit 5-4 of the AISI, the steel industry is receiving the technology developed in this project. They receive the technology by two means: 1) receipt of reports generated and 2) direct participation in the research. The AISI representatives provided technical direction to PNL about performance needs for the measurement system. They also provided some of the steel samples used in the project. To help cover PNL's cost of having AISI participate in the project, their private research contract was extended through FY 1987 with a small amount of additional funding.
- EMAT Vendor - The subcontractor selected to help develop high-temperature EMATs was Magnasonics, Inc. of Albuquerque, New Mexico. Magnasonics' participation in the technology transfer was important because they may become a commercial supplier of sensors when the technology is deployed in industry. Having a commercial source for sensors in place as the technology reaches maturity will aid in its attractiveness to potential industrial users. As part of Magnasonics' subcontract, they provided PNL with complete assembly drawings and schematics for the EMATs developed, thereby transferring the technology to the national laboratories.
- National Bureau of Standards - The NBS has been working in the area of high-temperature sensing with the AISI. Although their work has been limited to less than 900°C, they are developing a body of data correlating ultrasonic velocity with temperature for a variety of steels. These data were used by PNL to calculate internal temperature from ultrasonic velocity measurements.
- Pacific Northwest Laboratory - PNL transferred technology to the steel industry via monthly and topical reports and by inviting them to participate in the research at the laboratory. AISI representatives were also invited to attend project reviews and comment on project research plans. Follow-on work resulting from the PNL research will assist an AISI-member company in demonstrating the high-temperature sensing system on an actual continuous caster.

2.0 EXPERIMENTAL DEVELOPMENT OF HIGH-TEMPERATURE SENSOR

2.1 SYSTEM INSTRUMENTATION

A block diagram of the time-of-flight measuring system is shown in Figure 1. Besides the EMAT, the most significant components in the system are the pulsed laser, minicomputer, and digital oscilloscope. The laser is used to generate ultrasound pulses in the steel sample by lightly ablating its surface. With a pulse length of approximately 25 nanoseconds and pulse energy of several joules, a longitudinal-wave ultrasonic pulse is caused to travel the length of the sample. The ultrasonic pulse caused by the laser has a very short rise time, which makes it ideal for obtaining very precise time-of-flight measurements. In order to achieve the short pulses required for this project, a liquid dye Q-switch cell was added to the optical path of the laser. Other laser accessories installed included a power meter to measure laser output and a photo diode to sense the exact instant of laser firing.

An HP-9826 minicomputer has been programmed to control the laser firing and data acquisition sequence and to perform data manipulations. By responding to menu choices and prompts on the computer's screen, the researcher can perform the necessary system controlling functions. During a typical data acquisition sequence, the following information is recorded:

- Thermocouple Readings - As many as seven temperature measurements are recorded for each time-of-flight measurement. Typical thermocouple locations include sample center, sample surface, and EMAT internal.
- Received Acoustic Pulse - With time-zero corresponding to the instant of laser firing, the waveform of the received acoustic pulse is digitized, displayed, and recorded on disk by the Nicolet oscilloscope. From this recording, the time of flight of the acoustic pulse can be measured. A hardcopy of the digitized waveform can also be printed.
- Laser - A ruby laser was obtained on-site that has been adapted for use as an ultrasonic pulser. With the addition of a liquid dye Q-switch, the laser is now capable of reliably producing 25-nanosecond pulses with approximately seven joules of energy. Pulses generated by the laser exhibit very short rise time, so they are ideal for making the time-of-flight measurements. No further development work on the laser is expected.
- Minicomputer and Software - In order to acquire and keep track of the data generated by the project's experiments, a minicomputer has been set up to run on software designed for the purpose. The computer has been integrated with the laser, digital oscilloscope, printers, and the thermocouple data logger so that it controls the entire operating and data acquisition sequence. By responding to menu choices and prompts, the researcher can execute such functions as firing the laser, recording test results, printing test results, monitoring temperatures, or printing a temperature history.

FIGURE 1. Block Diagram of the Ultrasonic Time-of-Flight Measurement System

- Furnace - Early in the project, an electric tube furnace was obtained for heating the steel samples. After performing some initial experiments, it became apparent that the furnace would not be able to heat the samples' surfaces to the desired temperature of 1300°C. Therefore, another furnace was obtained that is capable of reaching 1430°C. This replacement furnace has an added advantage in that it has a liner built in with several small holes leading to the heating chamber. An inert gas supply can be attached to one of the small holes to prevent excessive scaling of carbon steel samples.
- Other Data - The computer records an abbreviated version of the acoustic waveform along with identification information such as time, date, and record number. This record also includes the thermocouple data described above.

Figure 2 is a photograph of the laboratory equipment used during the development of the high-temperature pulsed EMAT.

2.2 PULSED EMAT DEVELOPMENT

One of the key components required for a high-temperature velocity measuring system is an ultrasound receiver that survives in the severe thermal environment. Electromagnetic acoustic transducers (EMATs) were selected for this project for two primary reasons. First, because EMATs can be built without any plastic parts (as opposed to piezoelectric units), they lend themselves to adaptation for high-temperature applications. Second, EMATs require neither direct physical contact with the specimen under test nor an acoustic coupling medium, both of which makes them suitable for use with moving steel objects at high temperatures. For these and other reasons, EMATs are currently recognized as the most likely device for performing ultrasonic measurements at elevated temperatures on typical steel industry objects.

In order to obtain EMATs for this project, a subcontractor was selected to help develop them for very high temperatures. Magnasonics, Inc. of Albuquerque, New Mexico (President, Dr. George Alers) was awarded the subcontract to assist in EMAT development. They have significant experience in fabricating compact EMATs that operate at high temperatures. For example, Magnasonics supplied the EMATs that were used by the NBS in experiments to characterize the acoustic velocity properties of steels at high temperatures.

Early in the EMAT subcontract, a preamplifier was delivered to PNL so that instrumentation work could be carried out using a permanent magnet EMAT already on hand. With an internal sample temperature of 1140°C, the permanent magnet EMAT has been operated intermittently against a surface as hot as 900°C. No signal degradation was evident and the EMAT's internal temperature remained below 80°C; therefore, this EMAT could possibly be used intermittently at much higher surface temperatures.

For this project, the design goal was to develop an EMAT that would operate continuously on a steel object with a surface temperature of 1300°C. An EMAT with this performance capability would be useful for a wide variety of applications throughout the steel-making industry. The EMAT will include a

FIGURE 2. Laboratory Equipment Used During the Development of the High-Temperature Pulsed EMAT Receiver and EM Pulser Transmitter

preamplifier and any necessary support electronics so that it can be operated in conjunction with conventional ultrasonic testing equipment.

The approach taken for meeting the performance goal was to develop a pulsed electromagnet EMAT. In a pulsed EMAT, large magnetic flux is introduced into the test piece by a large current pulse (2000 amperes) flowing in the magnetizing coil. This large flux leads to greater sensitivity than would be possible with a conventional electromagnet of comparable size. The pulsed electromagnet approach, then, allows improved sensitivity with a compact device. For continuous operation at elevated temperature, the EMAT is water cooled. Ceramic materials are used for the EMAT housing and support structure with platinum and copper wires used for the eddy current and magnetizing coils, respectively. A cut-away sketch of the EMAT is shown in Figure 3.

The high temperature pulsed EMAT receiver developed in conjunction with Dr. Alers of Magnasonics, Inc. utilizes two pancake coils housed in a ceramic and steel heat exchanger unit. From this work, an "Application for a United States Patent on Electromagnetic Acoustic Transducer" was submitted by G.A. Alers, D.T. MacLauchlan, and L.R. Burns, Jr. of Magnasonics, Inc. The EMAT was designed for longitudinal acoustic wave detection. Impedance-matching and pre-amplifier circuitry were designed for 1-MHz acoustic detection. The pulsed coil is used to generate a magnetic field of 5.7 kilo-Gauss. The EMAT coil is used to detect the eddy current field generated by the acoustic waves. Three design iterations have been performed on the pulsed EMAT in order to optimize the heat transfer and signal response requirements for operation at 1300°C. The pulsed EMAT #3 is 8-inches long and 2.1 inches in diameter (see Figure 4). The heat exchanger uses water at 15 psig for cooling [8].

Appendix A is a copy of the technical paper "A Compact EMAT Receiver for Ultrasonic Testing at Elevated Temperatures," presented by Dr. Alers at the Review of Progress in Quantitative NDE Conference in Williamsburg, Virginia, June 1987.

2.3 THERMAL ANALYSIS

The high-temperature capabilities of the EMAT were investigated during the design stages. Temperature testing of the EMAT thermal capabilities was performed by monitoring the resistance of the EMAT coil during the application of heat. The resistance change resulting from the temperature increase was converted to temperature in Celsius. Three temperature curves for the pulsed EMAT receiver will be discussed.

Figure 5 shows a typical cooling rate for one configuration of the receiving EMAT. The time constant of the cooling and heating rate of the heat exchanger calculates contact times of 4 minutes before the steady-state temperature is achieved. Figure 6 shows the coil temperature and the hot steel surface temperature versus time during heating. From this data, the extrapolated temperature of the EMAT coil is estimated to be 700°C when the EMAT is in continuous contact with a hot steel surface of 1300°C. From this information, it was determined that the design of the heat exchanger portion of the EMAT would not be capable of continuous contact at the desired 1300°C. The breakdown temperature of the heat sink compound used in the EMAT was only 250°C and the

FIGURE 3. Cut-away Sketch of the Water-Cooled, High-Temperature, Pulsed EMAT #1

FIGURE 4. Pulsed EMAT Receiver for High-Temperature Operations (2.1-inch diameter by 8 inches long)

FIGURE 5. Cooling Curve of EMAT Receiver Coil Obtained by Monitoring Coil Resistance. The time constant is approximately 45 seconds.

FIGURE 6. EMAT Receiver Coil and Hot Steel Surface Temperature During Heating. The two curves are linear extrapolations to a steel surface temperature of 1300°C.

700°C temperature would cause a failure. Other heat sink compounds were evaluated and none found to be satisfactory. The present design has been successfully operated with continuous contact to 750°C surface temperatures. Above this temperature, the signal becomes noisy and the acoustic signal cannot be discriminated from the background (S/N less than 1).

Figure 7 shows a thermal cycle plot of the coil temperature versus time tested on the EMAT when the steel surface temperature was 1070°C. As can be seen from the data, a contact time of 30 seconds with 60 seconds cooling ensured that the EMAT coil temperature did not exceed 300°C. Using this information, momentary contact testing has been performed up to 1300°C on 304L stainless steel. The majority of the data discussed in the next section was obtained using contact times of 4 minutes or less.

2.4 EM PULSER DEVELOPMENT

The development of an electromagnet pulser to eliminate the need for a laser was initiated in the final quarter of the program. Early in EMAT development for this project, the subcontractor discovered that very large electromagnetic pulses could cause ultrasound to be generated in metal objects. Using this technique for ultrasound generation offers significant advantages over a laser: safer, more compact, less complex, and more rugged. All of these advantages would make the ultrasonic time-of-flight technology more attractive to industry because deployment would be much simpler and reliable. The high-temperature capability of the EM pulser transducer uses the same heat exchanger design of the pulsed EMAT receiver. Similar thermal capabilities of momentary and continuous contact are expected for the design. A first prototype EM pulser was fabricated and room-temperature operation was performed. High-temperature operation of the EM pulser/pulsed EMAT receiver was performed on a 304L stainless steel sample up to 1100°C. Results of this test identified that the thermal design should be reviewed to improve field hardenability.

FIGURE 7. Thermal Cycle Plot of EMAT Receiver Coil Temperature Using 30-Second Contact Against 1070°C Steel Surface and 60 Seconds Cooling

3.0 DATA ANALYSIS AND RESULTS

3.1 PULSED LASER/PERMANENT MAGNET EMAT RECEIVER RESULTS

During the initial stage of this phase of the project, a measurement system was set up using a permanent magnet EMAT. The permanent magnet EMAT receiver was used during the project to evaluate the high-temperature testing lab prior to receipt of the pulsed EMAT system. During one experiment with the permanent magnet EMAT receiver, a sample of 304L stainless steel was heated to an internal temperature of 1141°C and a surface temperature of 900°C. At regular intervals, ultrasonic time-of-flight readings were taken using the laser, permanent magnet EMAT, and computer-based data acquisition equipment. Representative results of the experiment are reproduced in Figures 8 through 11.

Figure 8 is a recording of the received ultrasonic signal at an internal temperature of 835°C. At this temperature, the ultrasonic pulse took 59.26 microseconds to travel through twelve inches of stainless steel. This time of flight corresponds to an acoustic velocity of approximately 0.206 in./microsecond, after correcting for the steel's coefficient of thermal expansion. This measurement, which is identified as "NIC6: TEST 8," was made at a surface temperature of 541°C. Notice that except for some interference during laser firing, there is essentially no noise in front of the first-received signal. The pulse has very short rise time and then some reflected or shear-wave signals follow it.

After a time-of-flight measurement is stored in the computer, the results can be printed out as in Figure 9. This record is from the same measurement as in the previous figure. The waveform stored in the computer, and printed here, is made by sampling one-tenth of the data points stored in the digital oscilloscope. It is recognizable as being the same signal as in the previous figure. Near the bottom of the figure is a nearly straight, horizontal line that is a recording of the laser signal. The laser pulse itself is not visible along the left edge of the chart because it is hidden by the extraneous spike in the ultrasonic waveform.

Printed above the chart is a listing of pertinent test data. The thermocouple readings are listed as TC 1 through TC 4 in degrees Celsius. TC 1 is the surface temperature of the stainless steel sample where the EMAT was located. TC 2 and TC 3 are internal temperatures of the stainless bar, with TC 3 located at the bar's mid-length. TC 4 is the temperature of the front surface of the EMAT. Printed above the temperature readings are the record identification, time, and date.

Figure 10 is a recording of the laser pulse and received ultrasonic signal that was recorded at an internal temperature of 1093°C. This measurement, identified as "NIC6: TEST 19," was taken at a surface temperature of 788°C. There are several important differences between this record and the one in Figure 8. At this elevated temperature, the time of flight has increased to 61.64 microseconds as a result of the ultrasonic velocity decreasing to approximately 0.199 in./microsecond. The amplitude of the first-arrival ultrasonic pulse has decreased slightly, although this record was made at the same amplifier gain. Notice that the signal-to-noise ratio is still greater than 20:1.

NIC6: TEST8

FIGURE 8. Digital Recording of an Ultrasonic Pulse Received at a Sample Temperature of 835°C, Permanent Magnet EMAT

DISK:FILE NIC6:TEST8 16 Oct 1986 (RECORD # 8) DATE:16 Oct 1986 TIME: 10:35:15
TC 1 = 541.26 TC 2 = 715.3 TC 3 = 835.51 TC 4 = 40.25

FIGURE 9. Computer Record of a Time-of-Flight Measurement Taken at 835°C, Permanent Magnet EMAT

Noise in front of the received pulse is the same, but the reflected and shear wave signals later in time have disappeared due to greater attenuation in the stainless steel bar.

Figure 11 is the computer record of NIC6: TEST 19 that contains the same type of information as Figure 9. In addition, below the chart is printed part of the temperature log that was recorded during the experiment.

From the results presented above, it can be concluded that the time-of-flight measurement system is capable of acquiring and storing experimental results at elevated temperatures. Further, the system is capable of resolving time-of-flight and signal-amplitude differences that result from heating a stainless steel sample.

3.2 PULSED LASER/PULSED EMAT RECEIVER RESULTS

The pulsed EMAT receiver developed for high-temperature operation has proved to be a viable technique for time-of-flight measurements of longitudinal waves. Figure 12 shows a typical signal response for a laser-transmitted acoustic signal through two inches of aluminum at 22°C. The lower signal is the pulsing coil current trace. When using a pulsed EMAT, knowledge of the approximate time-of-flight is required in order to position the peak magnetic field/peak current in the optimum position. As can be seen in Figure 5, six multiples of the longitudinal signal are detected. Figure 13 shows the typical results for a 10-inch-long 304L stainless steel sample at 507°C.

NIC6: TEST19 16 Oct 1986

FIGURE 10. Digital Recording of an Ultrasonic Pulse Received at a Sample Temperature of 1093°C, Permanent Magnet EMAT

DISK:FILE NIC6:TEST19 16 Oct 1986 (RECORD # 19) DATE:16 Oct 1986 TIME: 15:26:30
 TC = 787.69 TC 2 = 987.14 TC 3 = 1093.46 TC 4 = 51.93

TEMPERATURE LOG

DATE: 16 Oct 1986

TIME	TC1	TC2	TC3	TC4
14:57:51	817.56	961.52	1066.65	43.16
14 3:51	819.13	962.89	1067.79	42.99
14:59:51	820.65	964.31	1068.94	42.82
15:00:51	822.09	965.62	1070.10	42.65
15:01:51	823.47	966.95	1071.19	42.52
15:02:51	824.73	968.18	1072.27	42.36
15:03:51	826.02	969.39	1073.41	42.27
15:04:51	827.26	970.62	1074.47	42.16
15:05:51	828.49	971.79	1075.56	42.04
15:06:51	829.64	972.96	1076.59	41.94
15:07:51	830.73	974.11	1077.62	41.84
15:08:51	831.79	975.24	1078.59	41.78
15:10:37	806.35	975.43	1080.26	47.67
15:11:37	813.75	974.88	1081.19	46.87
15:12:37	817.63	974.79	1082.02	46.40
15:13:37	820.22	975.22	1082.81	45.96
15:14:37	822.27	975.88	1083.60	45.66
15:15:37	823.94	976.71	1084.43	45.31
15:16:37	825.47	977.63	1085.26	45.06
15:17:37	826.79	978.65	1086.10	44.81
15:18:37	828.02	979.67	1086.94	44.58
15:19:37	829.19	980.68	1087.79	44.38
15:20:37	830.28	981.58	1088.63	44.18
15:21:37	831.24	982.60	1089.45	43.94
15:22:37	832.20	983.53	1090.30	43.78
15:23:37	833.11	984.44	1091.10	43.62
15:24:37	833.94	985.28	1091.94	43.49
15:25:37	834.81	986.24	1092.74	43.34
15:27:46	816.36	987.54	1094.60	49.96
15:28:46	827.53	987.84	1095.48	49.01
15:29:46	834.63	988.68	1096.29	48.45
15:30:46	840.16	990.07	1097.07	47.98

FIGURE 11. Computer Record of a Time-of-Flight Measurement Taken at 1093°C, with a Partial Temperature Log, Permanent Magnet EMAT

FIGURE 12. Pulsed EMAT Receiver Response from Laser-Generated Acoustic Signal through 2 Inches of Aluminum at 22°C

FIGURE 13. Pulsed EMAT Receiver Response from Laser-Generated Acoustic Signal through 10 Inches of 304L Stainless Steel at 507°C

An interesting effect of the pulsed EMAT operation is the ability to detect Barkhausen noise in carbon steel samples. Figures 14a and 14b show the Barkhausen signal at 102 and 703°C (surface temperature). Above the Curie temperature for the carbon steel, the Barkhausen signal is gone (Figure 14c). The Barkhausen signal occurs due to the relaxation of the pulsed magnetic field used for the EMAT receiver.

The laser/pulsed EMAT system was used for time-of-flight measurements of several steel samples. Figures 15 through 18 are the temperature versus time-of-flight and amplitude data curves for 304L, 1008, 1018, and 4130 steel samples. All the samples were approximately 10 inches in length. Test results are consistent with the velocity calibration curves and amplitude attenuation of hot steel samples reported in other references [9,10].

Additional high-temperature tests were performed on a 4-inch-long sample of 304 stainless steel obtained from the continuous caster at the ARMC0 Stainless Steel Division, Baltimore, Maryland. Figure 19 shows the time-of-flight and amplitude data obtained from this sample. These data were presented at the Review of Progress in Quantitative NDE Conference in Williamsburg, Virginia, June 1987. Appendix B is a copy of this paper.

FIGURE 14. Pulsed EMAT Acoustic Signal in 4130 Carbon Steel Showing Barkhausen Noise Above and Below the Curie Point

b) 703°C

c) 762°C

FIGURE 14. Continued

FIGURE 15. Time-of-Flight and Amplitude Versus Temperature for 304L Stainless Steel Using a High-Temperature Pulsed EMAT Receiver and a Pulsed Laser Transmitter

FIGURE 16. Time-of-Flight and Amplitude Versus Temperature for 1008 Carbon Steel Using a High-Temperature Pulsed EMAT Receiver and a Pulsed Laser Transmitter

FIGURE 17. Time-of-Flight and Amplitude Versus Temperature for 1018 Carbon Steel Using a High-Temperature Pulsed EMAT Receiver and a Pulsed Laser Transmitter

FIGURE 18. Time-of-Flight and Amplitude Versus Temperature for 4130 Carbon Steel Using a High-Temperature Pulsed EMAT Receiver and a Pulsed Laser Transmitter

FIGURE 19. Time-of-Flight and Amplitude Versus Temperature for a 4-Inch Long, 304 Continuous Caster Sample Using a High-Temperature Pulsed EMAT Receiver and a Pulsed Laser Transmitter

3.3 EM PULSER/PULSED EMAT RECEIVER RESULTS

Room-temperature testing of the EM pulser transmitter and pulsed EMAT receiver was performed. Figure 20 shows the signal response of the pulsed EMAT receiver through 10 inches of stainless steel using the EM pulser transmitter. The signal-to-noise ratio is approximately 5 through this sample. The EM pulser/pulsed EMAT receiver system was also tested on a 6-inch-long 304L stainless steel sample. The maximum temperature achieved during this test was 1100°C. Momentary contact, less than 10 seconds, of both the transmitter and receiver sensors was used during this test in order to ensure optimum thermal operation. Figure 21 shows the time-of-flight and peak signal amplitude versus temperature for this test.

3.4 PARAMETERS AFFECTING ACOUSTIC VELOCITY MEASUREMENTS

During the testing of alloy 1018 carbon steel, it was found that the signal strength diminished above approximately 900° Celsius and that a thick oxide had formed. From these results, the effect of mill scale (oxide) on the acoustic measurement has been identified as an important factor for future steel plant operation of a temperature measurement system.

FIGURE 20. EM Pulser/EMAT Receiver Signal Response through 10 Inches of Stainless Steel

FIGURE 21. Time-of-Flight and Amplitude Versus Temperature for a 6-Inch-Long, 304L Sample Tested to 1100°C Using the EM Pulser/EMAT Receiver

The test results have shown that the pulsed ruby laser presently used does not ablate the blistering oxide growth off the test sample. Test results indicated that acoustic signals could be transmitted and received through a steel sample when the oxide was tightly attached and that the main problem occurs when the oxide became scaled or blistered. A blistered oxide will attenuate acoustic coupling to the bulk material preventing transmission of the ultrasound. Further study on why the acoustic signals above 900°C were not detected identified that the oxide coating was not the only cause of the signal attenuation. It should be noted that the signal was attenuated and masked by background noise and was not lost due to non-transmission.

A review of the literature on high-temperature EMAT testing showed that on mild steels, the longitudinal signal decreases slowly to 600°C, followed by a rapid increase in signal strength between 700° and 800°C and again followed by a rapid drop in signal amplitude above the Curie temperature. The decreased transmission amplitude above the Curie temperature has been attributed to magnetic state variations, crystal structure transformations, carbide solubility, and grain growth. The attenuation of acoustic energy at high temperatures is also dependent upon grain size, grain orientation, defects, and porosity [9,10]. Further fundamental metallurgical studies would be beneficial to the understanding of these mechanisms.

In a production temperature measurement system, the effect of the mill scale remains an important issue. One possible solution is the use of a more powerful laser to ablate the oxide off. A second and more suitable solution is to accept that the loose and blistering oxides need to be cleaned off of the surface. This can be achieved through the use of brushes or water sprays. Tight scales are a problem only if they prevent acoustic transmission. In tests performed at PNL on 4130 steel samples with as-received surfaces with a tight oxide scale present, there was no difficulty in using the laser/EMAT system. A simple test was performed at PNL using a one-inch-diameter oxide scale (0.02-inches thick). The scale piece was placed on the laser transmission side and a laser pulse was initiated. As expected, the EMAT did not receive the signal in this configuration. The oxide scale piece was then placed on the EMAT receiver side and a laser pulse was initiated. The received acoustic signal was attenuated proportional to the added lift-off distance of the scale, less than 1 dB.

Testing of acoustic transmission using a pulsed ruby laser has been found to be affected by the type of oxide present. It has been shown that the electromagnet (EM) pulser transmitter will not have the same difficulty. The laser transmitter is based on the principle of ablation for the generation of an acoustic wave. The EM pulser uses a magnetically generated force to transmit the acoustic wave. The EM pulser also has characteristics similar to an EMAT in that it can be operated with lift-off (typically less than 0.05 inches). The EMAT receiver is only affected by the oxide if it results in the lift-off becoming too great.

In conclusion, the mill scale should be removed from those steel products with excessive scale prior to the acoustic measurement. The scale can prevent reliable laser acoustic transmission and can potentially dirty the EMAT receiver system. Discussion with the AISI representatives indicates that the ability to clean off the scale is not a major problem.

A second parameter which will affect the acoustic velocity measurements is the requirement for accurate thickness measurement at the point of the acoustic measurement. In a meeting held at PNL in the fall of 1985, it was jointly agreed between DOE, AISI, and PNL that the issue of thickness measurement should not be pursued until a high-temperature acoustic sensor was developed. It was believed that commercially available systems could be engineered to perform the required measurement.

The resolution of an acoustic temperature system depends on the accuracy of the time-of-flight and the thickness measurement for the calculation of the acoustic velocity. In order to achieve a resolution of 10°C, the thickness measurement needs to be accurate to one part in 10,000 (e.g., 0.001 in 10 inches or 0.0001 in 1 inch). As pointed out by AISI representatives, conventional gaging in steel plants are not accurate enough to perform this measurement. However, the steel industry is presently using Optocators and other laser-based techniques for thickness measurements. One question which should be addressed is the surface roughness effect on a thickness measurement; for example, cast products typically have rough surfaces. The roughness will affect the temperature resolution achievable.

Two other effects on the thickness measurement are that the EMAT receiver averages the acoustic signals over approximately a one-inch area, and the thickness measurement may also need to average over the same area.

In earlier work at PNL, a manufacturer's search for optical gaging systems was performed. From that search, PNL visited Technical Arts, Inc. to evaluate a laser triangulation system. The Technical Arts system was tested on a heated nichrome wire to 1000°C showing no major measurement problem. This system was recommended as a potential thickness measurement system to be engineered for the high-temperature steel applications. Recently, a second company was found, Qualimatrix, which has manufactured a hot steel slab thickness system (maximum temperature unknown). These two commercial companies give justification to the statement that high-temperature thickness measurement systems can be developed.

It should be noted that at the present time, no system has demonstrated the required thickness measurement with the accuracy needed for the acoustic temperature measurement. The engineering and technology transfer of a thickness measurement system is necessary for the development of a thermal profile system.

The third issue to be addressed is the realistic ability to achieve a non-contact measurement. Under the present system, this question addresses two different sensors. The acoustic transmitter presently being utilized is a pulsed laser. This technique satisfies all the requirements for non-contact

application. Through the use of mirrors and beam confinement methods, the laser system can be placed away from the steel process equipment and can be operated in an industrial environment.

The EMAT receiver can be considered a non-contact sensor, which is dependent on the lift-off distance. EMAT sensitivity is best when the sensor is resting on the sample surface. With this constraint, it is best to accept that EMATs require light contact. In comparison to conventional piezoelectric acoustic transducers, the EMAT does not require a couplant, such as water or borax, or high pressure contact for acoustic coupling.

The requirement for light contact can be achieved by developing a mechanical fixture for holding and positioning the EMAT. Use of the EMAT for data acquisition has been performed in both continuous and intermittent contact. Many of the production application measurements would utilize momentary contact for the acoustic measurement and could move the sensor away from the hot steel billet between measurements.

4.0 ACCOMPLISHMENTS AND CONCLUSIONS

4.1 ACCOMPLISHMENTS

The completion of this program has resulted in several accomplishments and has provided insight into the required developments for the future. The major accomplishments of the final phases of this project include the following:

1. A laser/EMAT system has been constructed for the development of non-contact measurements of hot steel bodies. A pulsed EMAT has been designed for high-temperature operation on hot steel bodies using continuous contact up to 300°C and momentary contact up to 1300°C.
2. The 1-MHz pulsed EMAT receiver was able to detect time-of-flight longitudinal signals through 10 inches of stainless steel up to 1300°C, and carbon steels up to 900°C using the laser as a transmitter. The acoustic signal attenuation effects in the carbon steels are consistent with previous researchers results. The signal amplitude variations through the phase transition of ferrite to austenite are attributed to grain orientation and growth, crystal structure transformation, carbide solubility, and magnetic state variations [10].
3. The pulsed EMAT detected Barkhausen noise in the carbon steels below the Curie temperature.
4. PNL work included refinements to the pulsed EMAT design developed by Magnasonics, Inc. to increase the operating temperature for continuous contact.
5. A prototype high-temperature EM pulser transmitter was developed as a possible replacement for the pulsed laser.
6. EM pulser/pulsed EMAT receiver was tested on a 304L stainless steel sample up to 1100°C.

The current scope of work was to develop a sensor capable of detecting ultrasonic waves in steel at high temperatures. In pursuit of this task, PNL has developed an integrated system using a pulsed ruby laser transmitter, a pulsed electromagnetic acoustic transducer (EMAT) receiver, and electromagnetic pulser (EM) transmitter for the evaluation of acoustic behavior of ferrous materials as a function of temperature.

4.2 CONCLUSIONS

The following is a summary of the conclusions from this phase of the development of a high-temperature sensing system.

- A pulsed laser/pulsed EMAT receiver system has been demonstrated for measuring the time of flight of acoustic signals in hot steel samples. Attenuation and signal-to-noise ratio are important parameters to be monitored during actual high-temperature testing.

- A continuous contact EMAT application was not achieved. The thermal analysis of the pulsed EMAT receiver found that contact times of 5 seconds with cooling times of 45 seconds are required for use of the sensor at temperatures of 1300°C.
- The EM pulser/pulsed EMAT receiver system has been demonstrated for measuring the time of flight of acoustic signals in hot steel samples. Attenuation and the signal-to-noise ratio are also important to this system. Refinement of the EM pulser transmitter is required to improve the signal-to-noise ratio on coarse-grained continuous cast stainless steel samples.
- The prototype sensors and electronic circuitry developed during this project require field hardening and improved packaging before system reliability can be fully assessed. This engineering task is required to ensure optimization of signal-to-noise ratio, equipment reliability, and field hardening packaging for eventual steel plant environments.

5.0 RECOMMENDATIONS

During the course of the project, several potential future efforts have been suggested that lie beyond the current scope. These potential tasks are listed below.

- Demonstrate the System on a Continuous Caster - This is a highly desirable task to carry out because it will demonstrate that the time-of-flight measurement system works on objects that have a molten core. Further, because the demonstration will need to be carried out at a steel mill, it will serve as a prototype installation of the system in industry, and thereby help achieve the project's technology transfer goals. This project is now proceeding with a caster demonstration funded by DOE/OIP and cost sharing with AISI, and Magnasonics, Inc.
- Develop a Technique for Dimensional Measurement - The system currently under development at PNL is capable of measuring ultrasonic time of flight. This data can be combined with prior dimensional measurements to calculate ultrasonic velocity, which is the quantity needed to determine the average internal temperature. In an actual steel mill installation, however, dimensional information needs to be obtained at the same time and location as the time-of-flight data. The ideal way to make dimensional measurements of hot steel objects is with a non-contacting device. Such a device needs to be developed for operation at the high temperatures and harsh environment encountered in a steel mill.
- Develop an Algorithm to Calculate Internal Temperature Profile - The ultimate goal for this project is to be able to determine the internal temperature profile of hot steel objects, not merely the average temperature. To accomplish this, an algorithm needs to be developed that considers more than the ultrasonic velocity alone. Other factors that will need to be included in the temperature profile determination are data such as surface temperature and thermal processing history of the steel object.

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APPENDIX A

A Compact EMAT Receiver for Ultrasonic Testing at Elevated Temperatures

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A COMPACT EMAT RECEIVER FOR ULTRASONIC TESTING AT ELEVATED TEMPERATURES*

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INTRODUCTION

For the past several years, the AISI and several national laboratories have cooperated on a program to develop ultrasonic transducers that can be used in steel mills at the highest temperatures encountered during the processing of the solid metal {1}. To date, pulsed laser light focused on the surface appears to make a satisfactory generator or transmitter for ultrasonic pulses while the EMAT or Electromagnetic Acoustic Transducer appears to hold the greatest promise for the receiver {2}. Both of these essentially noncontact devices can be made to withstand the very hot environment and they are not very sensitive to the quality of the surface.

This paper describes the most recent developments in the design of an EMAT receiver to be used in conjunction with a pulsed laser for the measurement of the transit time of ultrasonic waves through a thick strand of steel as it emerges from a continuous casting furnace. The final device was tested at Battelle Northwest Laboratories by Boyd and Sperline and their results are described in another paper at this conference.

DESIGN CONSIDERATIONS

Ultrasonic Design

An EMAT or electromagnetic acoustic transducer {3} can detect the vibrations caused by an ultrasonic wave across an air gap by using an electromagnetic induction mechanism. The device itself consists of a coil of wire held close to the surface and a source of magnetic field to flood the region around the coil with magnetic flux. By choosing the direction of the magnetic field, the transducer can be made sensitive to either longitudinal or shear type waves. Theoretical predictions of the efficiency show that the air gap between the sensor coil and the work piece must be kept as small as possible and the magnetic field at the surface of the piece must be made as large as possible. Since it is well

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known that shear waves are highly attenuated in very hot steel {4}, longitudinal waves must be used for the present case so the magnetic field must be parallel to the surface. An operating frequency near 1 MHz appears to be high enough to retain adequate precision in the measurement of the arrival time of the acoustic pulse yet it is low enough to allow penetration of up to 10 inches of large grain size material {2}.

Magnet Design

Out of all of these acoustic requirements, the magnet to supply the EMAT's magnetic field is the most demanding because it must be actively cooled and should be made compact enough to be scanned over the surface of large billets. Common practice is to use a DC electromagnet equipped with pointed pole pieces to concentrate the magnetic flux to the region directly under the sensor coil. Although magnetic fields greater than 1 Tesla can be generated this way, the approach leads to small sensor coils and massive support structures that restrict the applicability of the EMAT concept.

Permanent magnets made out of the most modern alloys such as neodymium-iron-boron can be housed in water cooled jackets to make a very compact probe but the available magnetic fields drop to the range of 0.3 to 0.4 Tesla and the sensitivity therefore decreases by a factor of ten.

A third magnet design based on what might be characterized as a "brute force" technique arises when one utilizes the magnetic field close to a conductor carrying a very large current. It is well known that this field increases as the distance between the field point and the conductor approaches zero. In fact, classical formulae predict that 1 Tesla can be observed at the surface of a 2 mm diameter wire carrying 5000 amperes. Such a current is easily obtained for a short period of time by discharging a capacitor bank through the wire. It, therefore, seems practical to design a sensitive EMAT receiver using the configuration shown in Figure 1. Here, the magnetizing coil consists of several turns of heavy wire inside a water cooled box that not only removes the heat produced by the current pulse but also carries away the radiant heat from the steel. The pickup coil is placed directly under the magnetizing coil as indicated in the figure so that all the essential parts can be kept very close together and close to the work piece.

Since the pancake geometry of the magnetizing coil is very simple, a calculation of the tangential component of the magnetic field under such a coil was made as a function of radial distance from the central hole in the coil and with the air gap as a parameter. Even for a modest number of turns (20) and only a small current (500 amperes), fields greater than 1 Tesla were predicted for an air gap of one mm. To test the concept experimentally, a coil of 50 turns of 1/8-inch wide copper tape was wound with an I.D. of 1/4 inch and an O.D. of 1.6 inches. A simple gaussmeter was used to measure the field distribution around this coil and it was found that only 280 amperes were needed to generate a tangential field of 0.3 Tesla directly under the face of the coil.

Thermal Design

The flat layered structure of magnet and pickup coil shown in Figure 1 lent itself nicely to a calculation of the heat flow and temperature distribution that might be expected when the EMAT was in close contact to a steel billet at 2500°F (1360°C). For the calculation, thin layers of common insulating materials were considered at the interfaces between the key elements of the structure. It was assumed that a ceramic crucible material such as Mullite could be used at the front face of the EMAT and

Figure 1. Schematic diagram of the magnetizing coil, heat exchanger and sensor coil for a compact EMAT.

that thin layers of the alumina used as electronic circuit substrates could separate the copper conductors in the magnetizing and pickup coils. A metal can made from 60-mil thick titanium and filled with flowing water was assumed to extract the heat flowing from the steel through the structure. The calculations showed that all of the temperatures within the sandwich were well within the capability limits of the materials involved even though the front surface was at 2500°F (1360°C).

An EMAT probe that was actually constructed is shown in cross section in Figure 2. Here the magnetizing coil was placed in the flowing water on the inside of an alumina crucible whose bottom had been ground to a thickness of about 0.5 mm. The top of this crucible was closed by a stainless steel lid which held two stainless steel tubes for delivering and removing cooling water. It also had two holes through which the wires for the magnet coil passed. On the outside of this heat exchanger crucible, the EMAT sensor coil was attached with a high temperature cement and protected from the hot steel by a second alumina crucible with a thin bottom. Wires to and from the sensor coil were run up the side of the heat exchanger through the gap between the crucibles. At the top of the heat exchanger, these wires joined the leads to the magnetizing coil and ran out to the electronic circuits following the cold water inlet tube so that they could be kept cool. Since a considerable amount of heat load on the structure arose from the radiant energy emanating from the hot steel, the sides of the probe were insulated by Marenite rings held in place by a stainless steel tube that also acted as a handle for the total structure. Figure 3 shows a photograph of the completed probe disassembled to show the heat exchanger section next to the handle. A spring assembly in the handle pushed the front face of the probe lightly against the hot steel during operation.

Experimental tests using this structure showed that it could withstand contact with objects at even higher temperatures than the design

Figure 2. Cross sectional diagram of a water cooled EMAT probe used as an ultrasonic receiver on hot steel.

Figure 3. Photograph of a high temperature EMAT probe assembled from ceramic crucibles.

criteria used to establish the theoretical thermal gradients. This fortuitous circumstance occurred because in actual practice there was a thin air gap between the steel and the front face of the probe that introduced a very large thermal resistance and caused a very large temperature drop at the interface that separated the steel from the front face of the probe. Thus, the heat flow estimates used to calculate the operating temperatures of the parts of the probe were actually very conservative and choices of materials to be used in the construction of future generations of the device will be much easier.

Electronic Design

In order to exploit the high magnetic fields available to the pancake coil design, it was necessary to design a high current pulser circuit able to deliver a few thousand amperes to the magnet coil in a few hundred microseconds. This was accomplished by using a circuit based on the use of a commercial SCR that could withstand high voltages and high currents while still being able to respond in microsecond time intervals. This circuit also provided an adjustable trigger signal that allowed the pulsed magnet to be synchronized with the laser pulse to guarantee that the magnetic field would be at its maximum value when the acoustic pulse reached the EMAT.

Equally important to the operation of the system was a circuit to prevent the pulsed magnetic field from inducing voltages in the sensor coil that would completely saturate the preamplifier when it should be available for amplifying the small acoustic signals. This was accomplished by inserting a high pass filter at the input of the preamplifier to allow only the high frequency ultrasonic signals to enter the amplifier and to block the low frequency magnetic pulse from this path. Since the ultrasonic signals were near 1 MHz and the magnetic pulse was centered near a frequency of a few kHz, this filter did not have to be of a very special design.

Operating Results

The EMAT described above was tested on a sample of stainless steel 10-inches thick as it sat in a tube furnace at a temperature of 500 degrees centigrade (842 degrees Fahrenheit). Figure 4 shows the results in the form of two graphs as a function of time after triggering the pulsed magnet. The bottom graph plots the magnet current and shows that it reached a maximum value of 1400 amperes 30 microseconds after being triggered. Separate calibration measurements made at room temperature with an integrating fluxmeter indicated that the magnetic field associated with this maximum current was approximately eight kilogauss at the position of the steel surface. The top graph shows the output of the preamplifier connected to the sensor coil located between the magnetizing coil and the surface of the steel. Large, electromagnetic noise signals were observed both early and late in the time sequence when the time rate of change of the magnetic field was at its maximum and when there were switching transients in the timing circuits. The acoustic signal was recognized because it arrived at the correct time for a compressional acoustic wave produced by the laser impulse. Its rapid time variation and well defined leading edge make it quite suitable for deducing accurate transit times for ultrasonic waves in hot steel. More complete discussions of the results that have been obtained with this pulsed electromagnet, water cooled EMAT can be found in the paper by Boyd and Sperline elsewhere in this volume.

Figure 4. Ultrasonic signals generated by a pulsed laser in hot steel as detected by an EMAT receiver whose magnetic field was produced by the pulsed current waveform at the bottom of the figure.

Figure 5. Variation of the ultrasonic echo amplitude from the back surface of a 3-1/2-inch thick aluminum slab as a function of temperature.

A second use of this compact, high temperature EMAT could be for the detection of the so-called alligatoring that develops during the hot rolling of aluminum plate. As a cast billet is rolled into plate, the upper and lower surfaces deform more extensively than the center so that the corners extend outward to form a deep indentation that resembles the open mouth of an alligator. Continued rolling can leave a central discontinuity near the ends of the plate and this must be removed by shearing off of material in order to prevent it from being incorporated into the final products. Needless to say, it is very important to shear off only what is absolutely necessary and ultrasonic testing should be able to locate the exact extent of the crack if a transducer could be made to survive the temperatures involved. Feasibility tests with the EMAT described above indicate that it can easily meet these environmental requirements. Figure 5 shows some results obtained with the EMAT acting both as a transmitter and receiver on a 3-1/2-inch thick slab of aluminum alloy heated to near its melting point of 950°F (510°C). Plotted is the longitudinal wave signal amplitude as it was reflected from the back face of the slab as a function of temperature. Since these data were obtained without any coupling fluid and with the probe simply resting on the slab, it is clear that the transducer system has enough sensitivity to overcome the attenuation of the sound as the melting temperature is approached and that an echo from a discontinuity within the slab could easily be detected.

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APPENDIX B

Noncontact Temperature Measurements of
Hot Steel Bodies Using an Electromagnetic
Acoustic Transducer

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P. D. Sperline

Presented at Review of Progress in Quantitative NDE Conference,
Williamsburg, Virginia
June 1987

NONCONTACT TEMPERATURE MEASUREMENTS
OF HOT STEEL BODIES USING AN
ELECTROMAGNETIC ACOUSTIC TRANSDUCER

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NONCONTACT TEMPERATURE MEASUREMENTS OF HOT STEEL BODIES
USING AN ELECTROMAGNETIC ACOUSTIC TRANSDUCER (EMAT)

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INTRODUCTION

A noncontacting sensor system for measuring the average internal temperature of hot steel objects has been developed. The system uses a pulsed ruby laser for the generation of the acoustic wave and a pulsed Electromagnetic Acoustic Transducer (EMAT) as the receiver in a through-transmission technique. The pulsed EMAT design has been successfully tested to 1300° Celsius on a nine-inch-long stainless steel sample. The system measures the time-of-flight of the acoustic wave, which is coupled with the part dimension to determine the average acoustic velocity. From a calibrated relationship between velocity and temperature, the average sample temperature is determined.

The development of sensors and techniques for use in determining the internal temperature of hot steel bodies during production has been the major objective of this work. Use of a sensor capable of measuring internal temperatures would benefit the steel industry through cost reductions in energy and improved quality control [1]. The technique described in this paper is the use of acoustic velocity measurements. This technique has applications in the area of strand casters, slab reheating, and forging processes in steel production.

This project is to demonstrate a laser/EMAT acoustic velocity measurement system up to 1100°C or greater (1300°C desirable). The major effort has been the design iterations on the high-temperature EMAT sensor. This report will outline the laser/EMAT system for data acquisition and analysis, pulsed EMAT design, and the high-temperature testing of stainless and carbon steel samples.

PULSED LASER/PULSED EMAT SYSTEM

A system for obtaining time-of-flight measurements on hot steel objects has been set up in a laboratory. Key components of the system include a pulsed laser, furnace, minicomputer, thermocouple system, digital oscilloscope, and pulsed electromagnetic EMAT.

used to generate a magnetic field of 5.7 kilo-Gauss. The EMAT coil is used to detect time dependent changes in the magnetization caused by the acoustic waves. Three design iterations have been performed on the pulsed EMAT in order to optimize the heat transfer and signal response requirements for operation at 1300°C. The pulsed EMAT #3 is 8-inches long and 2.1 inches in diameter. The heat exchanger uses water at 15 psig for cooling.

Figure 2 shows a typical cooling rate for the EMAT receiving coil. The time constant of the cooling and heating rate of the heat exchanger allows momentary contact times of four minutes before the maximum steady-state temperature is achieved. The extrapolated temperature of the EMAT coil is estimated to be approximately 700°C when the EMAT is in continuous contact with a hot steel surface of 1300°C. The present design has been successfully operated with continuous contact to 750°C surface temperatures. Above this temperature, the signal becomes noisy and the acoustic signal cannot be discriminated from the background (S/N less than 1). However, momentary contact testing has been performed up to 1300°C on 304L stainless steel. The majority of the data discussed in the next section was obtained using contact times of four minutes or less.

NONCONTACT TEMPERATURE MEASUREMENT

Three topics of importance to the successful implementation of the internal temperature measurement technique using acoustic velocity are: available velocity temperature calibration curves for the different steels, acoustic attenuation effects at high temperatures, and the thickness measurement requirement for the acoustic velocity calculation. The National Bureau of Standards (NBS) has developed a system for obtaining the required velocity and thermal expansion calibration curves [7]. Through the technology exchange program, Pacific Northwest Laboratory has cooperated with NBS and the American Iron and Steel Institute (AISI) to obtain the required data. The velocity versus temperature curve for stainless steel is nearly a linear decrease from 5.7 mm/microsec at 22°C to 4.9 mm/microsec at 1100°C. Carbon steels show a deviation from linearity in the 600 to 800°C range due to the phase transformation from ferrite to austenite. The results obtained using the pulsed EMAT correlate with the NBS calibration data.

Acoustic attenuation effects have been studied by Kawashima, et al., and identify the importance of signal to noise in the through-transmission

Fig. 2. Cooling rate for pulsed EMAT showing time constant of 4 minutes

acoustic technique. Results show that the longitudinal wave amplitude for stainless steel begins to decrease above 700°C. Carbon steel longitudinal signals show a rapid signal increase above 700°C followed by rapid attenuation above 900°C. These results are consistent with data obtained using the pulsed EMAT.

The third topic for reliable temperature measurement is the requirement for thickness measurement. If the resolution requirement for internal thickness measurements is 10°C, then the thickness resolution must be approximately one part in one thousand. Two methods for thickness measurement can be used for the high-temperature testing. The first method is to make the required measurement at the temperature of interest. A second method is obtaining a room temperature measurement and calculating the thickness at the temperature of interest using the coefficient of thermal expansion correction.

RESULTS

The pulsed EMAT receiver developed for high-temperature operation has proved to be a viable technique for time-of-flight measurements of longitudinal waves. Figure 3 shows a typical signal response for a laser transmitted acoustic signal through two inches of aluminum at 22°C. The lower signal is the pulsing coil current trace. When using a pulsed EMAT, knowledge of the approximate time-of-flight is required in order to position the peak magnetic field (peak current) in the optimum time location. As can be seen in Figure 3, six multiples of the longitudinal signal are detected. Figure 4 shows the typical results for a ten-inch-long 304L stainless steel sample at 507°C.

An interesting effect of the pulsed EMAT operation is the ability to detect Barkhausen noise in carbon steel samples. Figures 5a and b show the Barkhausen signal at 102 and 703°C (surface temperature). Above the Curie temperature for the carbon steel, the Barkhausen signal is gone (Figure 5c). The Barkhausen signal occurs due to the relaxation of the pulsed magnetic field used for the EMAT receiver.

The pulsed EMAT has been used for time-of-flight measurements of several steel samples. Figures 6, 7, 8, and 9 are the temperature versus time-of flight and amplitude data curves for 304L, 1008, 1018, and 4130

Fig. 3. Pulsed EMAT receiver response from laser-generated acoustic signal through 2 inches of aluminum at 22°C.

steel samples. All the samples were approximately ten inches in length. Test results are consistent with the velocity calibration curves and amplitude attenuation of hot steel samples reported in the references [7,8].

Fig. 4. Pulsed EMAT receiver response from laser-generated acoustic signal through 10 inches of 304L stainless steel at 507°C.

Fig. 5. Pulsed EMAT acoustic signal in 4130 carbon steel showing Barkhausen noise above and below the Curie point.

Fig. 6. Time-of-flight and amplitude versus temperature for 304L stainless steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

Fig. 7. Time-of-flight and amplitude versus temperature for 1008 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

Fig. 8. Time-of-flight and amplitude versus temperature for 1018 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

Fig. 9. Time-of-flight and amplitude versus temperature for 4130 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

CONCLUSIONS

1. A laser/EMAT system has been constructed for the development of noncontact measurements of hot steel bodies. A pulsed EMAT has been designed for high-temperature operation on hot steel bodies using continuous contact up to 750°C and momentary contact up to 1300°C.
2. The 1-MHz pulsed EMAT was able to detect time-of-flight longitudinal signals through ten inches of stainless steel up to 1300°C and carbon steels up to 900°C. The acoustic signal attenuation effects in the carbon steels are consistent with previous workers' results. The signal amplitude variations through the phase transition of ferrite to austenite are attributed to grain orientation and growth, crystal structure transformation, carbide solubility, and magnetic state variations [8].
3. The pulsed EMAT detected Barkhausen noise in the carbon steels below the Curie temperature.
4. Future work on the noncontact sensing project includes the in-plant demonstration of the pulsed EMAT design on a continuous caster. This work is being pursued in cooperation with AISI at the Specialty Metals Division plant of ARMCO, Inc. located in Baltimore, Maryland.

Other work includes refinements to the EMAT to increase the operating temperature for continuous contact.

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