98

**In Plant Demonstration of High
Temperature EM Pulser and
Pulsed EMAT Receiver**

Final Report

**Experimental Development and
Testing of Ultrasonic System for High
Temperature Applications on Hot Steel**

November 1988

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

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A10
226-250	A11
251-275	A12
276-300	A13

PNL-6737
UC-312

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D. M. Boyd
P. D. Sperline

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Contract No. 13531

Pacific Northwest Laboratory
Richland, Washington 99352

EXECUTIVE SUMMARY

This report reviews the results of the In-Plant Demonstration of the EM pulser and pulsed EMAT receiver on a continuous caster strand. The plant demonstration of the high-temperature EMAT system was performed at the Baltimore Specialty Steel Company, Baltimore, Maryland on July 11-22, 1988. This program included the interaction of the American Iron and Steel Institute, Magnasonics Inc., and the Pacific Northwest Laboratory.

This work is in support of the overall objective of the Department of Energy to facilitate and increase energy conservation in the steel industry through the technology transfer of the high-temperature electromagnetic transducer (EMAT) for average internal temperature measurements of hot steel bodies. From the work performed under a prior Field Work Proposal, "Direct MEasurement of Solids: High Temperature Sensing," PNL Contract No. 10544, a high-temperature EM Pulser and Pulsed EMAT Receiver were developed.

The objective of this project was the demonstration of the high-temperature EMAT system on a continuous strand caster. Time-of-flight longitudinal acoustic data was obtained from a continuous caster strand in a steel plant environment.

In order to achieve these objectives, the laboratory EMAT system was field hardened and packaged for use at the steel plant. The EMAT system was integrated with a deployment mechanism designed and fabricated by AISI at the ARMCO Middletown facility. The completed system was shipped to the Baltimore Specialty Steel Company.

During the two weeks of plant testing trials, the system was successfully tested at three locations along the horizontal caster line. The first tests were after the cut-off station near the cooling rack for the steel billets. Surface temperatures, measured with an optical pyrometer, were approximately 760°C (1400°F). The second location was 44 feet from the mold face with a surface temperature of 871°C (1600°F). The final test location was 22 feet from the mold face at a surface temperature of 1123°C (2070°F). Time-of-flight measurements were made on three stainless steel samples: 1) 4 x 4 inch Type 304, 2) 6 x 8 inch Type 304, and 3) 4 x 4 inch Type 316. The results of the in-plant demonstration proved that the time-of-flight acoustic wave measurements could be obtained from hot steel continuous cast billets in a steel plant environment.

The next phase in the development of an average internal temperature measurement system includes additional testing on ferritic steels, development and testing of a thickness measurement system, and calibration data on additional grades of steel. The final objective of this program will be the integration of a complete system for the average internal temperature measurement and demonstration of the system in several different steel plant environments.

ACKNOWLEDGEMENTS

This work has been accomplished through the cooperation of many dedicated individuals. A major factor in the success of this project has been the technology transfer aspects of this project between the Department of Energy and the American Iron and Steel Institute (AISI). We would like to acknowledge the technical support, and the long hours in the Baltimore heat, of Dr. Bernard Droney, Dr. James R. Cook, and Mr. James Jackson.

This program has been administrated by the Office of Industrial Programs of the U.S. Department of Energy. Mr. Gene Eckhart has been the cognizant program manager at OIP and has provided continued support and guidance to this project. We would also like to acknowledge Mr. Don Segna and Mr. Paul Pak of the Richland Operations Office of the U.S. Department of Energy.

The authors would like to thank Kay Hass for her support in preparing the monthly reports and this report for publication.

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1.0 INTRODUCTION

This report describes work performed under the Field Work Proposal on the "In-Plant Demonstration of a High-Temperature EM Pulser and Pulsed EMAT Receiver" for the Department of Energy's Office of Industrial Programs. Cost sharing by the American Iron and Steel Institute (AISI) helped provide both technical guidance and equipment for the plant demonstration. This report covers the time period from January 1988 through September 1988.

Technical documentation of this project has been written and presented at two conferences. Appendix A is the paper by Boyd, et al., "In-Plant Demonstration of High Temperature EMAT System on Continuous Caster Strand," presented at the Review of Progress in Quantitative NDE Conference, La Jolla, California, August 1-5, 1988. Appendix B is the paper by Cook, Droney, and Jackson, "Ultrasonic Measurements in Hot As-Cast Billets: Field Testing of an EMAT-EMAT Approach to Sensing Internal Temperatures," presented at the Canadian Institute of Metals and Mining Conference, October 1988. These papers provide the major documentation of the testing of the EM pulser and pulsed EMAT receiver at the Baltimore Specialty Steel Company plant on the horizontal caster. A videotape made by AISI on the in-plant demonstration at the continuous caster is also available for viewing. Copies of the videotape are available from PNL, DOE/OIP, and AISI.

1.1 PURPOSE AND OBJECTIVE

This project is part of the long-term development of a non-contacting means for measuring the internal temperature profile of hot steel objects. The In-Plant Demonstration concept of this project was a result of the laboratory tests performed during the "Direct Measurement of Solids: High Temperature Sensing Program" completed December 1987 by the Pacific Northwest Laboratory [1]. This work is in support of the overall objective of the Department of Energy to facilitate and increase energy conservation in the steel industry through the technology transfer of the high-temperature electromagnetic transducer (EMAT) for temperature measurement of hot steel bodies.

The purpose of this R&D program is to aid the United States' metals industries in conserving energy by improving the energy efficiency of several energy-intensive production processes. Specifically, substantial energy savings are possible if the average temperature profile could be measured for hot bodies (e.g., ingots, slabs, blooms, or strands).

To achieve this program purpose, the objective is to demonstrate the ability of the EMAT receiver/EM pulser to survive the steel plant environment while providing time-of-flight information on a continuous strand caster. The continuous caster at the Baltimore Specialty Steel Company in Baltimore, Maryland has been chosen as the test site. The in-plant testing will be coordinated with the AISI Sensor Task Unit 5-4 through Drs. J. Cook and B. Droney, and Mr. J. Jackson.

Technology transfer of the high-temperature sensing system technology will allow the steel industry to apply this method to specific plant applications such as hot tubing wall thickness measurement, continuous caster monitor-

ing, and reheat furnace measurements. Each of these areas will lead to energy conservation through the use of temperature profile, average temperature, or time-of-flight measurements.

1.2 HISTORICAL SUMMARY

PNL has worked with OIP and the steel industry through the American Iron and Steel Institute 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 parallel funding and valuable in-kind services throughout the program.

From the work in FY86 a new design for a high-temperature pulsed EMAT was chosen after a review of the submitted proposals from potential subcontractors. A subcontract for the pulsed EMAT receiver was initiated with Magnasonics, Inc. PNL provided design review input on the materials used in the EMAT and made modifications to the design(s) to ensure high-temperature reliability. Three EMATs were purchased, the first two of identical design and the third with design modifications. During the early stages of the project, a pulsed ruby laser was obtained from the PNL loan pool. The laser was assembled and made operational after repair of the flash lamp. A computer control system was also assembled for the testing of the laser/EMAT time-of-flight measurements. Control software was written to integrate the Nicolet digital oscilloscope, laser, and thermocouple data acquisition system. Integration of the system was performed using the permanent magnet EMAT obtained at the end of FY85. A tube furnace was also obtained from the loan pool and made operational. Stainless steel samples were tested using the laser-generated acoustics and the permanent magnet EMAT with intermittent contact up to 900°C.

After the pulsed EMATs were received several temperature tests were run and design improvements for the high-temperature operation were made. The highest temperature test run was a surface temperature of 1300°C on a stainless steel sample. Continuous contact tests were performed on the first EMAT up to 1100°C with intermittent data taken up to 1300°C. The time-of-flight data obtained during these tests were used to calculate the velocity and average temperature of the samples. Further development of the pulsed EMAT design was identified after the signal-to-noise ratio decreased above 900°C. The noise problem was found to be caused by the thermal expansion differences of the materials causing the EMAT coil wire to vibrate during pulsing.

This work was completed with the laboratory demonstration of an EM pulser transmitter and pulsed EMAT receiver on hot stainless steel samples. The time-of-flight measurement system was demonstrated in the laboratory and proved the concepts for momentary contact for acoustic velocity measurement.

As a result of the interaction with AISI, it has been determined that the system should be demonstrated at a continuous strand caster in a plant environment. This new task will enhance the required technology transfer of an acoustic measurement technique for internal temperature measurement of steel.

2.0 IN-PLANT TESTING RESULTS

2.1 EMAT SYSTEM PACKAGING

The electronics to support the EM pulser and pulsed EMAT receiver were packaged into a fiberglass electronics rack. When closed up, the fiberglass rack was hermetically sealed to prevent ingress of dirt and other contaminants. All components were rack-mounted. The rack housed the pulser electronics, EMAT amplifier, time controller, and the required power supplies. The Nicolet digital oscilloscope was also rack-mounted.

During the preparation for packaging of the high-temperature EM pulser and pulsed EMAT receiver, several problems were encountered that required action to ensure that the laboratory system could withstand the harsh steel plant environment. During initial checkout of the timer control circuit, we identified poor timing stability. PNL electrical engineers identified non-optimum circuit layout of the timer controller. The circuit was re-wired and re-packaged into a TEK bin module. The original circuit was used as designed, but the layout and assembly were improved. This solved the timing problems.

On two of the PC boards for the high current magnetizer, the ground traces melted because of high current operation of the system. This was repaired by adding additional copper conductor to all high current traces on the PC boards. One time when the ground trace melted, a high voltage spike went through the control circuit and nine of the circuit chips required replacement.

Noise during the pulsing of the RF transmitter coil was identified and five days were spent locating the source. It was discovered that the nickel coil of the EM Pulser was arcing to the heat exchanger case. PNL designed a new RF pulser coil which was used in the final design of the EM pulser. A second noise source was identified as a transient during the operation of the RF pulser. The source of the noise was determined to be a voltage breakdown in one of the high voltage inductors. The inductor was taken off the PC board and unwound. The inductor core was wrapped with additional insulation to handle the high currents, new wire was wrapped onto the same core, and the inductor was replaced. This inductor is used on two other PC boards in the system which are operated at a lower voltage and have not been replaced.

During the packaging of the electronic components in the shipping cases, ground loops were encountered. The power supply for the RF pulser was replaced. Ground straps were added to minimize the noise from the ground loops.

Another problem was the fracture of the EM pulser ceramic faceplate, which required replacement of the coil assembly after one high-temperature test was performed at 1100°C. Ten spare alumina ceramic cups were purchased for use as spares for the Plant Trial. Five of the ceramic cups have had 0.05 inches machined off to decrease the lift-off distance and increase the signal amplitude. Thermal shock capabilities of the alumina were the primary problems.

Discussion with PNL Ceramicists concerning the thermal shock capabilities of ceramic materials suggested the use of a boron nitride ceramic. Samples

of the material were obtained and three faceplates were fabricated. Using the new material, the EM pulser was rebuilt using the original silver wire coil. A 304L steel sample was heated to 1275°C. The furnace used for this test did not allow for the through-transmission test to be performed. The EM Pulser was then thermally cycled against the hot steel surface and fired. Contact times of 5 seconds, during which eight waveforms from two 4-shot pulses were obtained, and cooling times of 120 seconds were used for the thermal test. Ten repeated cycles were run against the hot steel surface. At the end of the test, the EM pulser operation was verified by transmitting a wave through a room-temperature sample of aluminum and receiving it with an EMAT receiver. During the thermal cycle the faceplate did not crack.

New pulsed EMAT receiver coil/faceplate units were fabricated with 0.05-inch wall thickness from the boron nitride ceramic material. The new ceramic materials will be used during the field testing. The new PNL-designed RF pulser coil was used for the in-plant tests.

A 5-Hz, four-shot pulser circuit was designed and fabricated for the system. A pushbutton trigger was mounted in the timer controller bin, which when pushed gives four fire pulses to the EM pulser and pulsed EMAT receiver. The four-shot circuit was added to interface with the data acquisition capabilities of the Nicolet digital oscilloscope. The four A-scans can be stored to a Nicolet disk in less than three seconds. Signal processing such as averaging can be performed on the stored waveforms.

The problems encountered have been associated with high-temperature operation and system engineering. The prototype system uses high voltage and high current circuitry, nano-second timing, and requires operation in high temperature environments. The laboratory system modifications were implemented to minimize the potential problems to be encountered during the testing at the continuous caster.

The equipment was shipped to ARMCO Research and Technology, Middletown, Ohio for the integration of the EMAT system with the deployment system designed and fabricated by AISI.

2.2 SYSTEM CHECKOUT AT ARMCO MIDDLETOWN

The EM pulser and pulsed EMAT receiver system was shipped to ARMCO Research and Technology, Middletown, Ohio to check out and test the electronics and high-temperature sensors. The deployment system designed by AISI was integrated with the EMAT system. Laboratory tests were run on small sections of continuous cast stainless steel samples at elevated temperatures.

During the week of April 23-30, 1988, P. Sperline of PNL visited the ARMCO Research Facility in Middletown, Ohio to interface the high-temperature EMAT system to the mechanical deployment system. The deployment system included a hydraulic jack for positioning the EM pulser under the continuous cast billet. A manual boom was used for positioning the pulsed EMAT receiver. Visual alignment was used to ensure that the transmitter/receiver pair were properly positioned for data acquisition.

The 4-inch-long, fine-grained 304 stainless steel sample was heated to 2000°F (1100°C) overnight. Hot test data was taken on a 4.25-inch-diameter, 3-inch-long ARMC0 round sample and on the 2-inch-diameter, 6-inch-long, fine-grained 304 stainless steel sample. The equipment was left at the ARMC0 facility for additional testing by AISI.

AISI personnel performed several hot tests on cast and rolled materials at 1800, 2000, and 2075°F. The boron nitride faceplate appears to have solved the thermal shock cracking problem. The high-temperature results showed some signals were detected; however, signals were too noisy to allow averaging. During one of the tests, the receiver coil insulation failed. In order to repair the receiver and provide a system overview and checkout, Dan MacLaughlin of Magnasonics was contracted to provide a service call on May 11 and 12. A trigger signal from the RF pulse was added to the system for improved reliability.

In order to ensure success at the in-plant test AISI ordered spare PC boards and sensors from Magnasonics.

The schedule for the in-plant test was set for July 11-22, 1988. The equipment was packed onto a rental truck and driven to the Baltimore Specialty Steel Company, Baltimore, Maryland.

2.3 IN-PLANT TEST ON CONTINUOUS CASTER

The in-plant demonstration of the high-temperature EM pulser/pulsed EMAT receiver system was performed during the period of July 11-22, 1988.

The two-week testing period of the system included several field modifications to the laboratory system. The majority of the modifications were related to the temperature requirements of the system and included upgrade of the water cooling lines, special cooling of the Nicolet oscilloscope and electronics rack, addition of forced air cooling for the RF pulser box, and repositioning and cooling of the remote preamplifier. Other minor problems encountered during the testing included repair of a loose stripline connection of the EM pulser, replacement of the EMAT receiver with a spare after a short occurred in the coil, and difficulties with the manual alignment of the sensors during data acquisition.

The high-temperature EMAT system was operated at three locations along the continuous strand caster. Time-of-flight data was taken near the cooling table (surface temperature of 1400°F), 44 feet from the mold face (surface temperature of 1600°F), and 22 feet from the mold face (surface temperature of 2070°F). The following steel types were tested during the two weeks of testing:

- 4-inch x 4-inch 304 stainless steel
- 6-inch x 8-inch 304 stainless steel
- 4-inch x 4-inch 316 stainless steel

Additional details on the results of the tests are provided in the two technical papers found in the Appendices. A videotape made by AISI of the testing at the continuous caster is also available. Copies have been provided to PNL and DOE/OIP.

3.0 ACCOMPLISHMENTS AND CONCLUSIONS

3.1 ACCOMPLISHMENTS

The successful demonstration of the High-Temperature EMAT System on the continuous caster showed that time-of-flight measurements could be acquired for the velocity calculations required for internal temperature determination. The major accomplishments of this project included the following:

1. The EM pulser and pulsed EMAT receiver system was demonstrated on a continuous caster in a steel plant environment.
2. The time-of-flight measurements were obtained on stainless steel continuous cast billets up to surface temperatures of 2070°F.
3. The EMAT system allowed measurements to be obtained on a moving continuous cast strand.

3.2 CONCLUSIONS

The following is a summary of the conclusions from the in-plant demonstration of the EM pulser and pulsed EMAT receiver system:

- The laboratory EM pulser and pulsed EMAT receiver electronics equipment was demonstrated in a steel plant environment; however, additional field hardening is required of a system before it could be used in a steel plant for extended or permanent measurements.
- Future deployment systems need to ensure that the alignment during data acquisition is within 0.5 centimeters to ensure optimum signal response is obtained.
- On-line thickness measurements are required for the calculation of the velocity.
- Calibration curves of velocity versus temperature are necessary for each steel grade.
- Lower frequency longitudinal waves (0.5 MHz) should be considered for the highly attenuative steel grades.

4.0 RECOMMENDATIONS

Several future research projects were identified during the performance of this project. The following is a list of possible tasks:

- Testing the EM Pulser/Pulsed EMAT Receiver on Ferritic Steel - The majority of the testing was performed on stainless steel samples. Testing needs to be performed to determine the applicability of the EM pulser/EMAT receiver system on ferritic steels. Early testing indicated that the phase transition occurring at approximately 800°C resulted in reduced signal amplitudes attributed to the phase change and possible oxide coatings.
- Develop a Technique for Dimensional Measurement - The system currently measures the time of flight of acoustic signals through the hot steel bodies. This data needs to be combined with a thickness measurement in order to calculate the acoustic velocity and the determination of the average internal temperature.
- Develop a Complete Average Internal Temperature Measurement System - A complete system with thickness measurement and time-of-flight measurements needs to be developed. The system should integrate the EM pulser/pulsed EMAT receiver, a thickness measurement system, a data acquisition system for velocity calculation, a calibration data base for average internal temperature determination, and a system controller to allow data input and output for process control monitoring.

REFERENCES

1. D. M. Boyd, G. E. Spanner, and P. D. Sperline. 1988. Direct Measurement of Solids: High Temperature Sensing: Final Report, Experimental Development and Testing of High Temperature Pulsed EMATs, PNL-6537, Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A

IN-PLANT DEMONSTRATION OF HIGH-TEMPERATURE EMAT SYSTEM ON CONTINUOUS CASTER STRAND

IN-PLANT DEMONSTRATION OF HIGH-TEMPERATURE
EMAT SYSTEM ON CONTINUOUS CASTER STRAND

D. M. Boyd
B. D. Droney (a)
P. D. Sperling
J. F. Jackson (b)
J. R. Cook (b)

August 1988

Presented at the Review of Progress
in Quantitative NDE Conference
La Jolla, California
August 1-5, 1988

Work supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

-
- (a) Bethlehem Steel Corporation
Homer Research Laboratory
Bethlehem, Pennsylvania 18016
(b) ARMO Research and Technology
Middletown, Ohio 45043

IN-PLANT DEMONSTRATION OF HIGH-TEMPERATURE

EMAT SYSTEM ON CONTINUOUS CASTER STRAND^a

D. M. Boyd and P. D. Sperline
Pacific Northwest Laboratory
Operated by Battelle Memorial Institute
Battelle Boulevard
Richland, WA 99352

B. D. Droney
Bethlehem Steel Corporation
Homer Research Laboratory
Bethlehem, PA 18016

J. F. Jackson and J. R. Cook
ARMCO Research and Technology
Middletown, OH 45043

INTRODUCTION

The Pacific Northwest Laboratory (PNL) has been working with the Office of Industrial Programs of DOE and the American Iron and Steel Institute (AISI) since 1983 to develop a sensor that can determine the internal temperature of hot steel bodies. Research projects utilizing the relationship between acoustic velocity and temperature have been the primary technique investigated. The techniques most recently used have been laser-generated stress waves and EMAT systems [1,2,3]. Development of an ultrasonic sensor that can measure the acoustic velocity at high temperatures has been the major effort over the past few years. The internal temperature of steel bodies can be determined by measuring the time-of-flight through a known distance to calculate the velocity, and from the relationship between temperature and velocity, the average internal temperature can be determined [4,5].

A non-contact sensor system for measuring the time-of-flight of longitudinal acoustic waves of hot steel objects has been developed. Working with Magnasonics, Inc., the high-temperature capabilities of the pulsed EMAT receiver and EM pulser were developed. The sensors were laboratory tested on hot steel surfaces up to 2300°F [6,7].

The objective of this phase of the high-temperature sensing project for the steel industry is to demonstrate the ability of an EMAT system to survive the steel plant environment while providing time-of-flight measurements on a continuous strand caster. Arrangements with

^aWork supported by the U.S. Department of Energy (DOE) under Contract DE-AC06-76RLO 1830.

the Baltimore Specialty Steel Corporation were made to use their stainless steel continuous caster. PNL provided the high-temperature EMAT electronics, and AISI provided the mechanical deployment equipment for the test.

During the period of July 11-22 1988, the High Temperature EMAT System was tested at the continuous caster in Baltimore. During the demonstration, the equipment was operated at three locations along the caster strand: after the flame torch cut-off with 1400°F surface temperatures, 44 feet from the caster mold face with 1600°F surface temperatures, and 22 feet from the caster mold face with surface temperatures in excess of 2000°F. The surface temperatures were measured using an optical pyrometer. Time-of-flight measurements were made on three stainless steel samples: 1) 4 x 4 inch Type 304, 2) 6 x 8 inch Type 304, and 3) 4 x 4 inch Type 316. The results of the in-plant demonstration proved that the high-temperature EMAT system was capable of measuring the time-of-flight of acoustic waves and operating in a steel plant environment.

This paper will review the high-temperature EM pulser/pulsed EMAT receiver equipment and the results of the in-plant test performed at the continuous caster at the Baltimore Specialty Steel Corporation, Baltimore, Maryland.

CONTINUOUS STRAND CASTER

The continuous strand caster used for the testing and demonstration of the high-temperature EMAT system is located at the Baltimore Specialty Steel Corporation plant in Baltimore, Maryland. Figure 1 shows the mold face of the horizontal continuous caster with a 4 x 4 inch strand of steel being drawn. The operation of the caster has three major systems: the tundish, mold, and horizontal table. The tundish holds the molten steel which is fed into the mold. The mold provides the shaping and cooling to form the continuous cast billets. The horizontal table includes the billet extractor equipment, flame torch cut-off for cutting billet lengths, and cooling rack for the billets.

Fig. 1. Beginning of continuous cast run showing the mold face of the continuous caster at the Baltimore Specialty Steel Corporation plant

Continuous cast steel production time varied from two to eight hours depending on the number of furnace heats and steel types. The testing of the high-temperature EMAT system did not interfere with the steel production.

HIGH-TEMPERATURE EMAT SYSTEM

The laboratory high-temperature EM pulser and pulsed EMAT receiver system was packaged for use at the continuous caster. Figure 2 shows the electronics package with the transmitter and receiver EMAT/EM pulser pair in contact with a section of a continuous cast steel billet. The components of the EMAT system include a digital oscilloscope for RF waveform data acquisition, high voltage power supplies, magnetizer circuit, and amplifier circuits. The laboratory equipment was packaged into the two shock-mounted equipment racks for shipping and operation at the continuous caster.

Details of the pulsed EMAT and EM pulser design have been described in other reports [6,7]. Modifications from the equipment described in those reports include improved thermal shock material for the EMAT faceplates and the addition of a pre-amplifier. Additional thermal shielding for the equipment was also added at the plant.

The deployment system used for the data acquisition on the continuous cast billets was provided by AISI. The EM pulser was mounted in a hydraulic jack, which allowed the operator to manually raise the transmitter into contact with the billet. The pulsed EMAT receiver was mounted in a boom that was manually lowered into contact with the billet. Visual alignment of the transmit/receive pair was used during data acquisition. Figure 3 shows the transmitter jack and the receiver boom positioning the EMAT and EM pulser onto a steel billet sample.

IN-PLANT TESTING RESULTS

A typical testing sequence for the time-of-flight data acquisition on the continuous cast billets was achieved through the following sequence. The hydraulic jack was activated to raise the EM pulser into contact with the bottom of the hot steel billet. Simultaneously, the

Fig. 2. High temperature pulsed EMAT system packaged for in-plant demonstration

Fig. 3. Deployment system used for positioning the high temperature EMAT sensors. System checkout prior to hot steel measurements.

EMAT receiver was manually lowered using the boom into contact with the top of the hot steel billet. Figure 4 shows the sensors in contact with a steel billet from the continuous caster with a surface temperature of approximately 1600°F. After the transmit/receive pair were in contact with the hot steel surface the pulsed EMAT and EM pulser fire button was pushed to sequence four consecutive shots in less than two seconds. The four RF waveforms were then automatically recorded onto the disk of the digital oscilloscope. A second four-shot pulse was then fired and recorded or the sensors were moved out of contact with the hot steel billets. Cooling time for the sensors was two to five minutes between measurements to ensure the heat exchanger cools the coils used in the EMAT and EM pulser.

During the in-plant testing, three test locations with increasing surface temperature were used to record the time-of-flight data. Normal plant operation for production output of the continuous caster was maintained during the in-plant testing project. The EMAT deployment system was positioned on the caster line between heats. Once the caster production began, the equipment could not be moved. Time-of-

Fig. 4. High temperature pulsed EMAT and EM pulser in contact with 4x4 in. steel billet during continuous cast. Positioned 44 feet from mold face. Surface temperature 1640°F.

flight data was recorded on the hot steel billets provided during the standard production runs and included 316 and 304 grades of stainless steel.

Prior to each testing sequence on the continuous caster, a fine grained rolled 304 stainless steel calibration block was used to test the signal response and data acquisition sequence of the system. Figure 5 is the RF waveform obtained from the system after the test performed 22 feet from the mold face. This waveform represented typical operation of the EMAT system and demonstrated the survivability of the equipment from both the radiant and convective heat from a steel billet with a surface temperature of 2070°F.

The test locations along the continuous caster included measurements near the cooling table after the flame torch cut-off with surface temperatures of 1400°F, 44 feet from the mold face with surface temperatures of 1600°F, and 22 feet from the mold face with a surface temperature of 2070°F. Full data reduction of the RF waveforms has not been completed. Unaveraged RF waveforms are presented here to represent the capability of the high-temperature EMAT system to operate in the plant environment on the hot continuous caster billets. Figure 6 shows the received time-of-flight signal through a 4 x 4 inch 304 stainless steel billet with a surface temperature of 1200°F. Other hot steel billet tests included a 6 x 8 inch 304 steel billet at 1265°F, and a 4 x 4 inch 304 steel billet at 1640°F. Figure 7 shows the RF waveform for a 4 x 4 inch 316 steel billet 22 feet from the mold face at a surface temperature of 2070°F.

During the testing of the EMAT system when it was located 22 feet from the mode face, time-of-flight data was obtained on the 316 steel billet as it was cooling. At the completion of a casting run, the horizontal extractor equipment stops pulling the hot steel billet out of the mold. With the steel billet stopped, cooling begins immediately. During this time, several time-of-flight RF waveforms were obtained. Figure 8 shows the time-of-flight versus temperature recorded during the billet cooling. The data shows the time-of-flight decreasing with lower steel temperatures as expected.

Fig. 5. Pulsed EMAT receiver response for the 4 inch, fine-grained 304 stainless steel calibration block

Fig. 6. Pulsed EMAT receiver response for a 4x4 in. 316 continuous cast steel billet 22 feet from the mold. Surface temperature 2070°F.

Fig. 7. Pulsed EMAT receiver response for a 4x4 in. 304 continuous cast steel billet after the flame torch cut-off. Surface temperature 1200°F.

Fig. 8. Time-of-flight versus temperature for the 316 stainless steel continuous cast billet 22 feet from the mold. Data taken at the end of the cast when the billet is stationary for several minutes.

CONCLUSIONS

The high-temperature pulsed EMAT and EM pulser system was successfully tested at a continuous caster on steel billets in excess of 2000°F. The system was tested on several steel grades at three equipment locations along the continuous caster strand. Signal-to-noise ratios of better than 2:1 were obtained without signal averaging. Operation of the prototype EMAT system in the plant environment helped to identify several field-hardening improvements necessary for a permanent high-temperature EMAT system.

Data reduction for the velocity determination, signal averaging, and internal temperature determination will be completed on the results from this in-plant testing project. The thickness measurements required for the velocity calculations were obtained from the steel billets after they cooled.

The final steps for production use of an internal temperature measurement system for hot steel bodies will couple the high temperature EMAT system with an on-line thickness measurement system.

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APPENDIX B

ULTRASONIC MEASUREMENTS IN HOT AS-CAST BILLETS:
FIELD TESTING OF AN EMAT - EMAT
APPROACH TO SENSING INTERNAL TEMPERATURES

Presented at the CIM 27th Annual Conference
of Metallurgists, Montreal, Quebec, August 28-31, 1988

**ULTRASONIC MEASUREMENTS IN HOT AS-CAST BILLETS:
FIELD TESTING OF AN EMAT - EMAT APPROACH TO SENSING INTERNAL TEMPERATURES**

J. R. Cook*, B. E. Droney, and J. F. Jackson***

*** Armco Inc., Armco Research & Technology, Middletown, OH**

**** Bethlehem Steel Corporation, Bethlehem, PA**

ABSTRACT

This paper will comment on the field testing of a prototype sensing system for monitoring internal temperatures in solid and solidifying materials. The system was developed as part of an ongoing collaboration among AISI member companies, the U. S. National Bureau of Standards and Battelle's Pacific Northwest Laboratories. The approach uses "non-contacting" electromagnetic acoustic transducers (EMATs) in a transmitter and receiver combination to monitor ultrasonic times-of-flight (TOF). That data can be related to the internal temperature distributions in as-cast materials. The field testing demonstrated the viability of the EMAT approach: the device survived difficult mill conditions and successfully acquired data from moving, as-received strand cast materials with surface temperatures in excess of 1130 Celsius.

KEYWORDS

Hot connection, direct rolling, direct connection, internal temperature, sensors, EMAT, EMPulser, automatic control, process control, ultrasonic, field testing, prototype, solidifying, non-contacting, as-cast.

INTRODUCTION:

Our American Iron and Steel Institute (AISI) Collaborative Task Unit (CTU) has just completed a demonstration of the EMAT-EMAT approach to ultrasonic monitoring of hot as-cast billets in a steel mill environment. This demonstration was the concluding phase of a multifaceted effort to develop the technological basis to meet a critical need: sensing the internal temperature distribution in solid and solidifying bodies of steel.

The effort has been truly collaborative - involving active participation by eight different steel companies (1), the U. S. National Bureau of Standards (NBS), and Battelle's Pacific Northwest Laboratory (PNL). The work has been supported by AISI member contributions, the U.S. Department of Energy and the U.S. Department of Commerce.

HOT CONNECTION: SENSOR REQUIREMENTS

One of the steel industry's overriding concerns is to improve the coordination of processing and scheduling to take full advantage of the known yield, quality, productivity and energy advantages of hot connecting and direct rolling strand cast material.

Specific sensors which would aid materially in accomplishing these goals have been detailed (2). Ideally, these sensors would survive mill environments and function in real-time on as-produced materials receiving no special surface preparation. A priori knowledge of material properties, processing history and any conceivable ancillary measurements of surface temperatures, dimensions, etc. might be incorporated. The sensors have to provide reliable information in a cost-effective manner, and induce no unusual hazards to processed materials or personnel. Those sensors would:

- . enhance control of strand casting processes to ensure metallurgical quality and maximize residual energy content,
- . determine the workpiece temperature distribution before either direct rolling or reheating,
- . monitor workpiece temperature profiles during reheating to optimize furnace heating and pacing conditions,
- . estimate workpiece profiles for dynamic optimization of rolling and finishing processes.

PROCESS CONTROL: THE SENSOR GAP

The AISI had developed a comprehensive list of sensors which would substantially improve processing efficiencies (3). Some fell into a class for which no known sensing approach existed. Our AISI collaborative task unit (CTU 5-4) was organized to promote the development of a sensing approach which could meet some of the sensing requirements for hot connection: the determination of the temperature distribution in hot solid and solidifying materials. The task unit leveraged AISI member financial contributions, helped coordinate the technical efforts, and is now transferring this technology to the industry.

It was understood from the beginning that this would be a high risk undertaking. The profit motive was not in the sale of sensor systems or components, but in the use of the sensor system to monitor and control processes more precisely. The sole intent was to develop and demonstrate candidate technologies which instrument manufacturers or system integrators might be willing to exploit and bring to full commercialization.

INTERNAL TEMPERATURE SENSING: THE METHOD EVOLVES

Both eddy current and ultrasonic methods have been shown effective in interrogating internal temperature distributions. Each method relies on material parameters that have a definable and reproducible temperature dependence and each requires a mathematical reconstruction to extract the apparent temperature distributions. Sensitivities can be influenced by numerous material parameters (e.g. grain size, texture, strain, porosity, etc.) and these influences will prove useful in other sensor applications.

The eddy current approach depends strongly on electrical conductivity and geometric shape and is well suited to aluminum. The approach may also prove workable on steel products above the Curie temperature.

Ultrasonic approaches rely mainly on the measurable dependence of ultrasonic velocity with temperature (Fig. 1). The velocity can be determined from the ratio of two measured variables: the ultrasonic path length and time-of-flight (TOF). Each must be monitored accurately and simultaneously or at the same location under identical conditions.

The collaborative effort progressed through distinct phases with intensive developmental efforts at NBS and PNL, hardware integration and testing at ARMCO Research, and the very recent field testing on a commercial horizontal continuous caster at Baltimore Specialty Steel Corporation (BSSC).

a. "Proof of Concept" and Beyond (NBS)

The scientific basis for the ultrasonic approach was developed under the auspices of the Research Associate Program at NBS (4,5). That work demonstrated the "proof of concept" and emphasized:

- . studies of ultrasonic sensors including pulsed lasers, conventional piezoelectric transducers, and various EMAT designs,
- . the generation of reference data on the variation of ultrasonic velocity with temperature in different grades of steel,
- . the laboratory measurement of ultrasonic TOFs in reheated samples of cylindrical and rectangular bodies of steel to 800 Celsius,
- . the development of algorithms to reconstruct temperature distributions from such information,
- . the integration of these components into a laboratory test fixture capable of determining and displaying internal temperature profiles in near real-time.

NBS continues to pursue collateral technologies in signal processing and error analyses and some uniquely innovative surface wave and dimensional resonance approaches. They are currently addressing the difficult problem of mapping the location of the solidification boundaries using molten core aluminum analogs of steel alloy systems.

b. Hot EMAT Receiver Design and Testing (PNL)

A complementary effort at PNL concentrated on sensor development (6) and on technology transfer. The primary goal was the development and delivery of a fieldable prototype hot EMAT sensing system. This effort led to the development of a simple, inexpensive EMAT receiver capable of continuous application on steel samples with surface temperatures in excess of 1300 Celsius.

The EMAT approach is in principle non-contacting but just barely: signal strength decreases exponentially with liftoff distance (Fig. 2). Although liftoff distance of up to 1 cm are possible, a few mm is more usable and still sufficient to reach into the base material through scale and surface irregularities.

To apply ultrasonics using EMATs, the workpiece must be amenable to inspection with conventional ultrasonic equipment (1 MHz range) with no large voids or inclusions. Variations in surface conditions (undulations, heavy scale, etc.) may limit applicability due to reduced signal-to-noise and uncertainty in ultrasonic path lengths.

Recent work at PNL has sought to improve the thermal tolerance of the EMAT designs. This has been accomplished through clever temperature tolerant coil designs, integrated water cooled heat exchangers, ceramic face-plate designs, and modifications to the associated electronics (7). Substantial improvements in heat tolerance, long term survivability, and signal processing are yet possible.

c. EMAT (EMPulser) Supplants Laser Transmitter

The original approach at both NBS and PNL used a laser to generate the ultrasonic pulses. This type of pulse is convenient in a laboratory environment, being temporally and spatially precise and highly reproducible. The use of a laser in a mill environment is entirely feasible but adds considerably to the system cost and complexity and obliges special training and safety precautions.

During early testing, a Magnasonics-supplied EMAT receiver was modified to act as a transmitter (8). Generating sharp electromagnetic impulses, this EMAT transmitter (EMPulser) successfully launched ultrasonic pulses into the hot steel. Although signal strengths were greatly reduced, this approach was very attractive because it supplanted the laser and considerably reduced the system cost and technical complexity. The reduced signal strengths were combated with refined EMAT and preamplifier designs, and clever signal processing approaches. The EMPulser idea, borrowing much of the technology already developed for the EMAT receiver, was an intriguing option, and recognized as such by our task unit. The combined EMPulser-EMAT receiver was specified for the subsequent field trials.

d. System Assembly (Hot EMAT - EMAT)

The prototype EMAT-EMAT system was assembled in shippable cases and tested prior to shipment at PNL. The system included several spare EMAT components, coils, refractory elements, etc. (Fig. 3). Real-time data acquisition and signal processing capability were provided by a Nicolet 4094A digital processing oscilloscope and an H-P plotter. Data could be stored on floppy discs for later analyses with the Nicolet or other computers using appropriate software.

Excellent signal-to-noise ratios were obtained in tests on aluminum reference blocks, and on fine grained (rolled or forged) ferritic steel samples. Poorer signal-to-noise ratios were obtained on coarse grained as-cast samples, obliging special signal processing. This circumstance forewarned that the projected field trials on a horizontal caster would present severe testing conditions.

The control electronics (Fig. 4) included hardware to generate multiple pulses with intermediate data acquisition and storage. This multiple data acquisition approach was needed so that time averaging and other signal processing techniques could be applied to improve marginal signal-to-noise ratios. Requisite signal/noise were obtained in the laboratory on various samples of material at temperatures in excess of 1300 Celsius.

Laboratory testing also demonstrated that pulsed EMATs required judicious practices: on ferromagnetic samples Barkhausen noise caused by magnetic domain motion

had to be eliminated; stable timing circuits were needed to synchronize the three pulse circuits used in the EMPulser-EMAT system, to adjust timing for different sample lengths, and to provide an accurate time-zero reference for TOF measurements.

e. Integration and Field Testing (ARMCO Research & Technology)

The equipment was packaged and shipped to Armco Research & Technology for further refinement and integration with an actuation system destined for use on the Baltimore Specialty Steel Corporation (BSSC) horizontal caster (Fig. 5). Innumerable improvements and revisions were made to the system and performance improved to the point at which useful signals could be obtained on cast stainless steel samples without multiple shot averaging. Signal-to-noise on samples of the BSSC material exceed our minimum 3:1 requirement; the ratio on low carbon cast billets approached 50:1.

The specific aims of this phase of the effort were:

- . to engineer the EMAT-EMAT handling and deployment subsystems,
- . to choreograph operating procedures which avoided damaging equipment and experimenters,
- . to conduct further hot tests on various materials of interest,
- . to fully test all components and spares.

The actuation systems consisted of independently operated fixtures for the EMPulser and EMAT receiver. The EMPulser was located below the sample and articulated into position by means of an air cylinder; the EMAT receiver was suspended above the workpiece on the end of a counter-balanced beam. Reflective heat shielding was used to protect wiring, water hoses, and electronic equipment from heat radiation.

The EMPulser air cylinder would be activated, gradually bringing the EMPulser into contact with the bottom of the workpiece; simultaneously, the lever arm would be manipulated so that the EMAT receiver would contact the top, and the data acquisition and storing sequence would begin. At the end of the acquisition cycle both EMPulser and EMAT would be retracted. The entire sequence would be repeated at intervals dependent on the sample temperature.

REAL WORLD TESTING: HORIZONTAL CONTINUOUS CASTER

The equipment was transported to the BSSC test site and staged at a series of monitoring points progressively closer to the casting machine. The test team included participants from AISI, PNL, Magnasonics as well as support personnel from BSSC.

In order to complete our commitment to select and oversee the development of candidate technologies it was important to demonstrate that the EMAT sensors could survive and be effective in a real world environment. Although path length sensors of requisite accuracy are commercially available, none was included in the plant trials: the emphasis was to demonstrate EMAT survivability and the ability to detect signals with adequate signal-to-noise. We captured ultrasonic waveforms at temperature (Fig. 6) and performed elementary signal processing to extract the

TOF data. The billets were interrogated as received and no special surface preparation of any kind was attempted. Some billet dimensions were measured subsequently using mechanical micrometers.

Our initial installation on the horizontal caster was at a location in-line just after the cutoff torch and before the cooling bed. Surface temperatures ranged from 650 to 760 Celsius. The EMAT sensors were placed in contact with the head and tail ends of successive bars momentarily stopped at our inspection station.

Good results were obtained: clear signals were resolved in the as-cast 10 cm X 10 cm product, and the TOF data clearly indicated the expected temperature difference between the front and tail ends of the bars (Fig. 7). Processing and analyses of these data are in progress, and no attempt to reconstruct temperatures has been attempted pending the availability of proper calibration curves. We subsequently tested 15 cm X 20 cm product and found marginal signal-to-noise ratios; off-line signal processing on these stored data was used to extract TOF data.

The system had proven successful at this location, but our goal was to test the limits of that success even to failure of the EMAT device. Accordingly, we moved the installation upstream to within 14 m of the mold. Radiant heat loading on equipment was noticeably higher; strand surface temperatures were in the range of 870 Celsius. Although the EMATs survived intact, electronic equipment, including the Nicolet computer, which were designed to operate primarily under laboratory conditions, began to suffer heat related failures.

Considerable effort was expended in improving the heat tolerances of various components: more heat shielding, relocating the preamplifier, forced air cooling for pulser and electronic components, a borrowed air conditioner for the main electronics cabinet. These enhancements proved effective and no further heat related failures were experienced.

After adequate TOF data were acquired at the 14 m location, the equipment was reinstalled within 7 m of the mold face: strand surface temperatures were 1100 - 1150 Celsius. Our first test proved unsuccessful: the signal-to-noise ratio was too low to extract usable data. We subsequently determined that this particular alloy (an ARMC0 proprietary grade) could not be inspected by conventional ultrasonic methods even at room temperature due to a peculiarly high acoustic attenuation.

We successfully acquired TOF data on the next available heat just prior to plant shutdown; surface temperatures exceeded 1130 Celsius. At the end of cast the bar was repeatedly interrogated as it cooled and the dependence of TOF on bar temperature was clearly resolved (Fig. 8).

SUMMARY

The hot EMAT approach developed to solve this problem is a generic approach to the broad class of sensing problems accessible by ultrasonic techniques. The EMAT approach offers particular benefit for monitoring properties in difficult and marginally accessible locations. Versions of this EMAT might be applied to direct in situ nondestructive evaluation (flaw detection), characterization of material properties, residual stress or texture. Here, the method provides ultrasonic data for measuring the internal temperatures in strand cast blooms without surface preparation.

The hot EMAT-EMAT sensing system proved viable in the field trials on a horizontal continuous caster. The test conditions were a severe test of the EMAT-EMAT approach and we were satisfied that the system survived and usable signals were extracted. Based on laboratory inferences, we anticipate much improved signal-to-noise ratios on as-cast carbon steels and on rolled and forged (fine grained) products.

FUTURE WORK: SYSTEM ENGINEERING CAVEATS

Success of the EMAT-EMAT approach for temperature measurements in other hot charge applications will depend on how effectively the various system components can be engineered for the severe environmental conditions and precise measurement requirements. Key items to be considered include:

- . inducing the initial impulse into the sample (EMPulser),
- . detecting the pulse upon arrival (EMAT receiver),
- . a reliable and accurately aligned transducer handling mechanism,
- . path length determination,
- . calibration (velocity dependence on temperature),
- . rapid real-time signal acquisition,
- . signal processing, storage and retrieval,
- . algorithmic reconstruction of temperature distribution (for many hot charge applications average temperature may suffice),
- . presentation of pertinent results.

We believe that working in concert with NBS and PNL we have made significant progress on each of the requisite components of such measurement systems. Additional effort by PNL and NBS are clearly warranted; our task is to encourage this further development and to promote commercialization of this technology.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the contributions of Don Boyd, Paul Sperline, Gary Spanner, and Doug Lemon (PNL), Haydn Wadley, Steve Norton, and Floyd Mauer (NBS), Don MacLauchlin and George Alers (Magnasonics), the members of the AISI collaborative task unit, and numerous other individuals who supported our efforts.

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- Fig. 1: Longitudinal ultrasonic velocity dependence on temperature. A nearly linear dependence is found with austenitic 304 stainless steel. A more complex dependence with noticeable hysteresis is found on ferritic 1018 steel.
- Fig. 2: EMAT receiver and EMpulser sensitivities show exponential dependences on liftoff distance. Liftoffs of up to 1 cm can be used, but a few mm is more practical and usually sufficient to overcome surface irregularities and scaling conditions.
- Fig. 3: Photograph of the PNL EMAT receiver and EMAT pulser just prior to shipping to Armco Research. Also shown are the power supplies, control and data acquisition equipment mounted in shippable containers for field testing.
- Fig. 4: Block diagrams of signal and timing blocks for EMAT-EMAT signal detection and storage. Three separate pulsing circuits with associate time controllers are needed.
- Fig. 5: Photographs of the Armco Research laboratory arrangement showing the EMpulser and EMAT receiver delivery systems in the data acquisition position on a reheated billet.
- Fig. 6: Photograph of the EMAT Receiver and EMAT pulser contacting 10 cm x 10 cm stainless steel billet on Baltimore Specialty Steel Corporation horizontal continuous caster. Some billets were marked for later verification of dimensions.
- Fig. 7: Data acquired in sequential tests of the leading and trailing ends of one 10 cm x 10 cm cast billet. The shift between traces indicates a difference of more than 100 Celsius in internal temperature between front and tail of the bar. Measured surface temperatures were 650 and 760 Celsius.
- Fig. 8: Cooldown curve acquired by repetitively interrogating last bar produced at end of cast. Ultrasonic transit times sensitive to the internal temperatures are plotted against surface temperatures measured by handheld pyrometer. The dependence is surprisingly linear.

EMAT-EMAT System on Stainless Steel

Block Diagram of EMAT-EMAT Data Acquisition System

8-13

B-14

B-15

EMAT System on Horizontal Caster Hot Tests On-line after Cutoff

EMAT System on Horizontal Caster

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