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

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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

[a]Work 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.

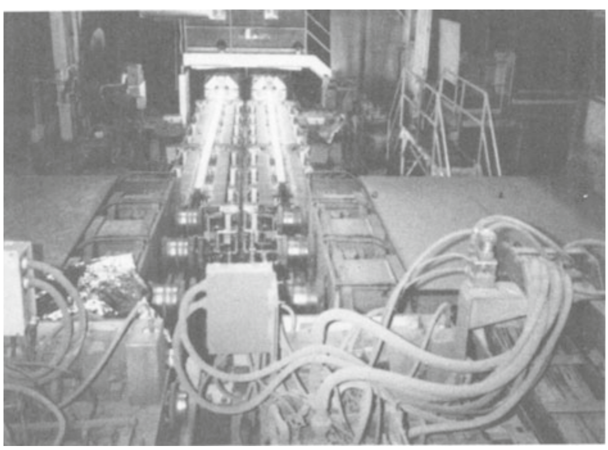

Fig. 1. Beginning of continuous cast run showing the mold face of the continuous caster at the Baltimore Speciality Steel Corporation plant

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

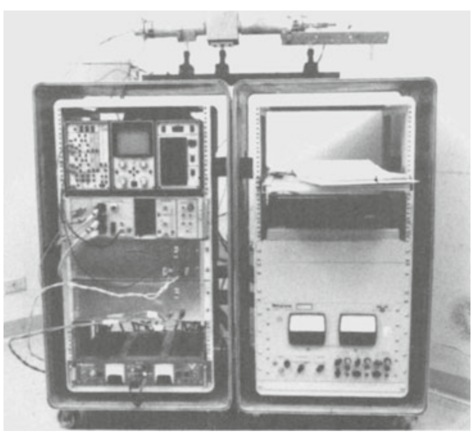

Fig. 2. High temperature pulsed EMAT system packaged for in-plant demonstration

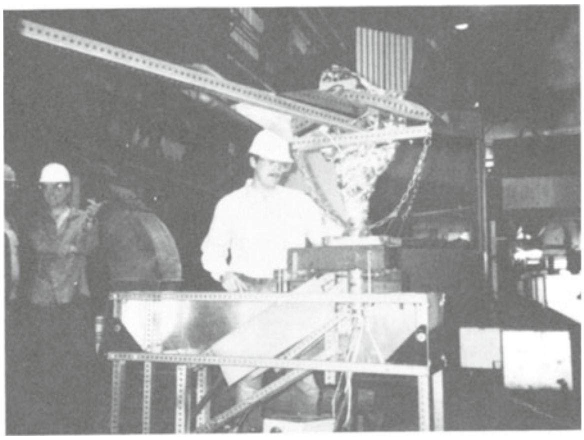

Fig. 3. Deployment system used for positioning the high temperature EMAT sensors. System checkout prior to hot steel measurements.

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-

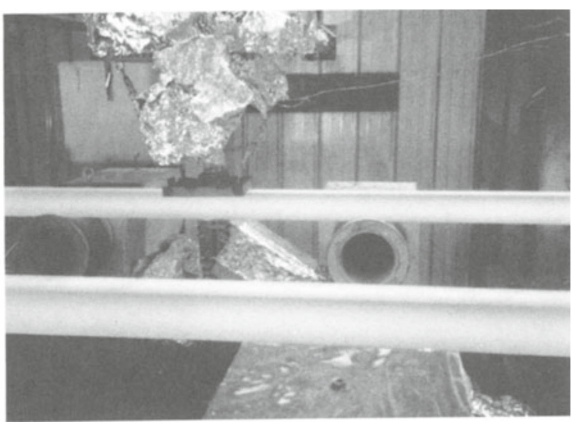

Fig. 4. High temperature pulsed EMAT and EM pulser in contact with 4x4 in. steel billet during continuous cast. Positioned 44 feet from mold face. Surface temperture 1640°F.

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.

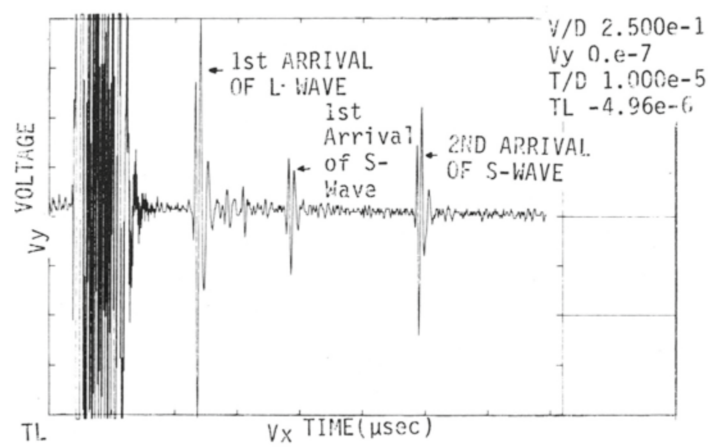

Fig. 5. Pulsed EMAT receiver response for the 4 inch, fine-grained 304 stainless steel calibration block

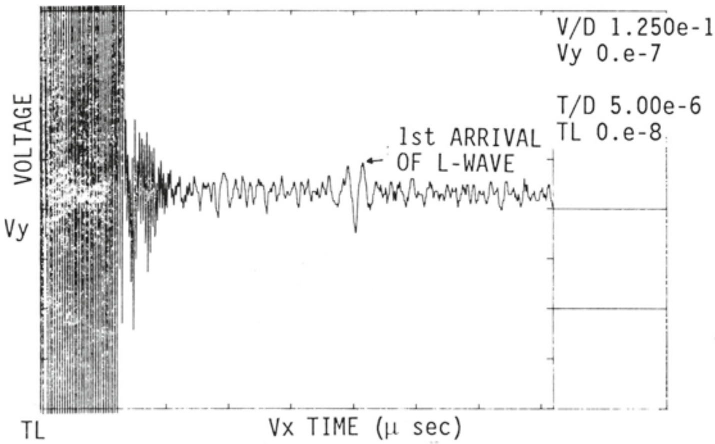

Fig. 6. Pulsed EMAT receiver response for a 4x4 in. 316 continuous cast steel billet 22 feet from the mold. Surface temperature 2070°F.

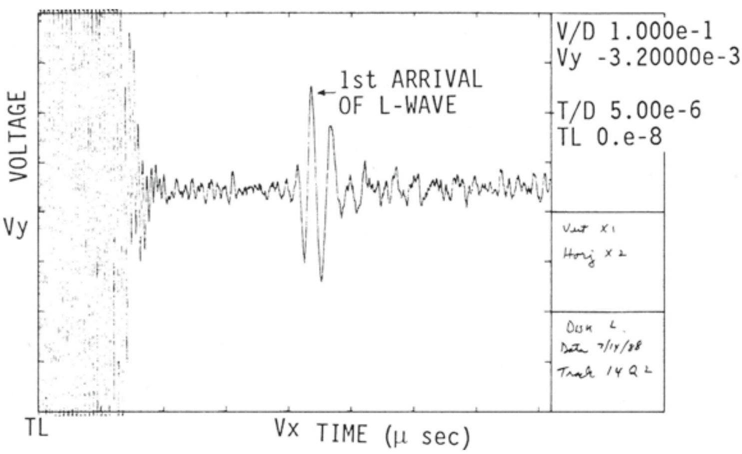

Fig. 7. Pulsed EMAT receiver response for a 4x4 in. 304 continuous cast steel billet after the flame torch cut-off. Surface temperture 1200°F.

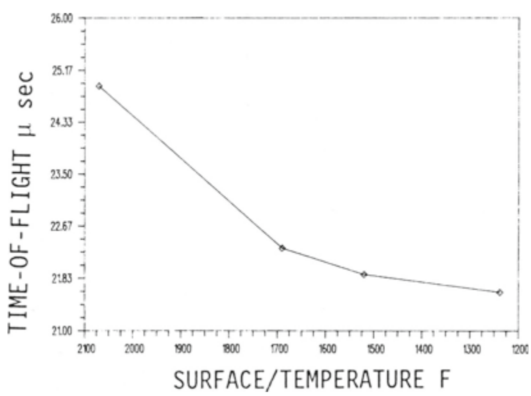

Fig. 8. Time-of-flight versus temperature for the 316 stainless steel continuous cast billet 22 feet from the mold. Data taken at the end of the cast when the billet is stationary for several minutes.

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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