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

Donald M. Boyd and Paul D. Sperline

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

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.

Previous work on the use of a laser/EMAT system has demonstrated acoustic velocity measurements up to 810°C [2]. As pointed out in the work by Alers and Wadley, the development of an EMAT capable of momentary operation up to 1300°C is feasible. This report will discuss the development and testing of an EMAT achieving this goal. The advantages of EMATs for high-temperature operation include lift-off and controlled acoustic mode detection. Details of EMAT operation and advantages can be found in several publications [2,3,4].

The pulsed laser was utilized as the source for an acoustic wave transmission. Acoustic wave generation using a pulsed laser source is a well understood technique [5] and has been used in high-temperature applications [2,6]. A pulsed ruby laser with a liquid dye Q-switch (cryptocyanine) was used for this work. The longitudinal wave acoustic generation was achieved using pulsed laser energy to cause surface ablation.

A glow bar furnace allowing a maximum temperature of 1500°C was used for heating the steel samples. A 3/4-inch hole in the back of the furnace provided access for the laser pulse. Test samples 10 inches long by 2.5 inches in diameter were used during the testing. Temperature monitoring of the furnace and the steel samples was achieved using thermocouple temperature recording for up to six channels on the minicomputer data acquisition system.

The data acquisition and control system included a HP9826 minicomputer and Nicolet digital oscilloscope. Figure 1 shows a block diagram of the complete system used for the high-temperature testing of the EMAT.

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. 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

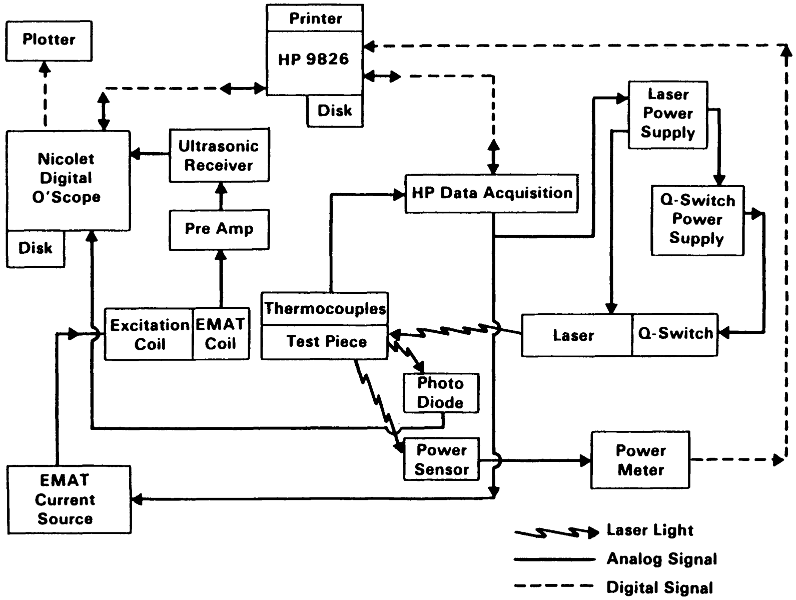


Fig. 1. Laser/EMAT ultrasonic velocity measurement system

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 then 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

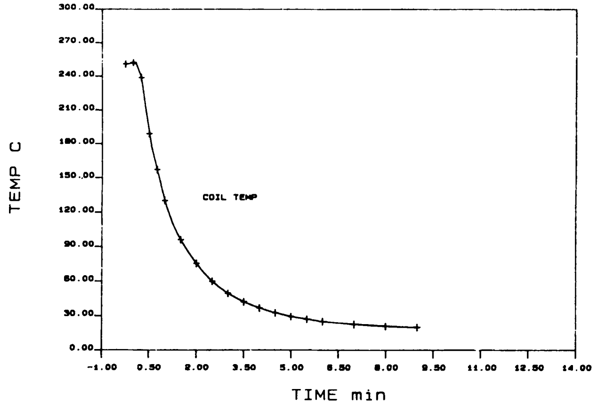


Fig. 2. Cooling rate for pulsed EMAT showing time constant of 4 minutes

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

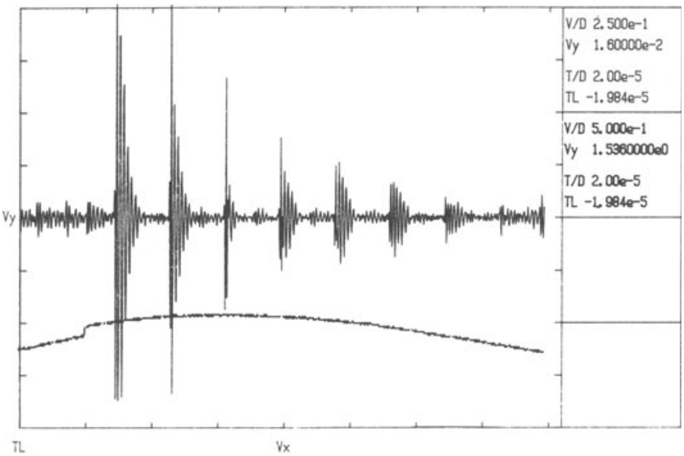


Fig. 3. Pulsed EMAT receiver response from laser-generated acoustic signal through 2 inches of aluminum at 22°C.

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].

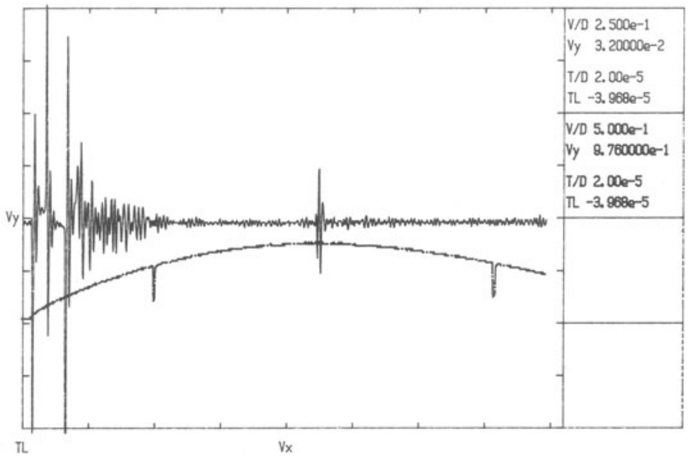
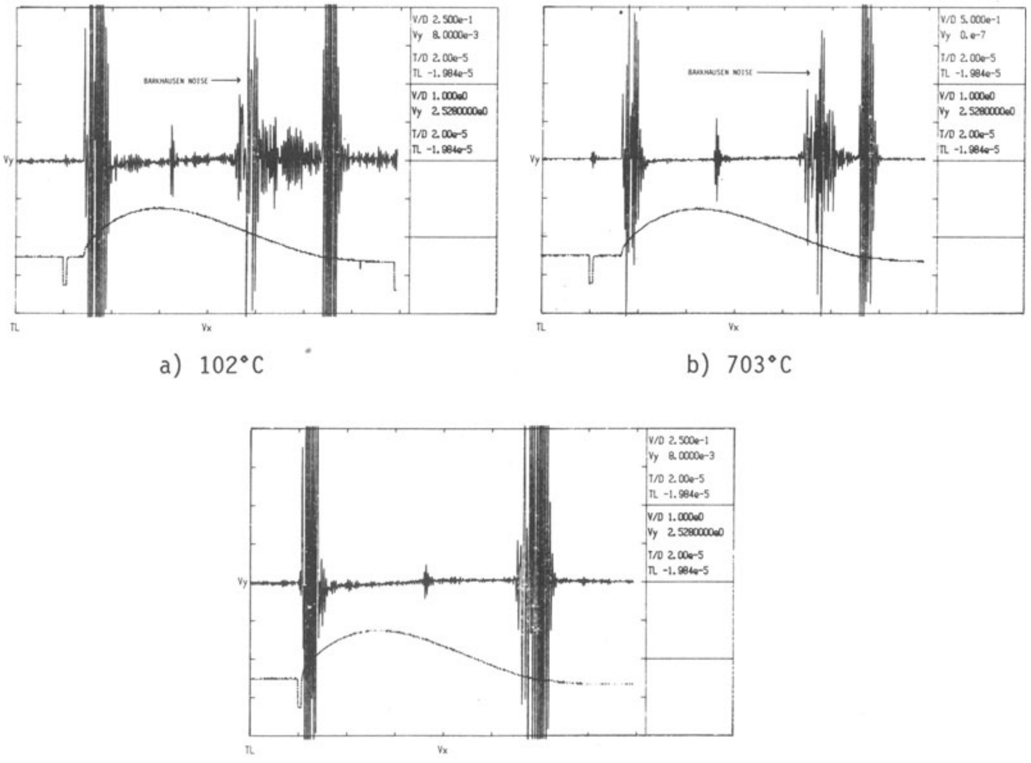


Fig. 4. Pulsed EMAT receiver response from laser-generated acoustic signal through 10 inches of 304L stainless steel at 507°C.



a) 102°C

b) 703°C

c) 762°C

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

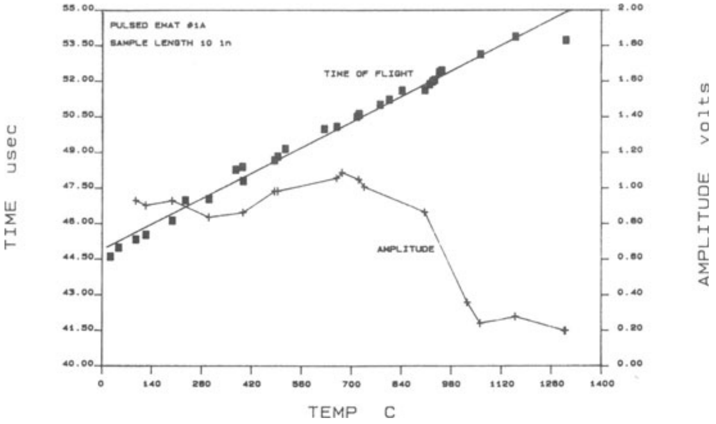


Fig. 6. Time-of-flight and amplitude versus temperature for 304L stainless steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

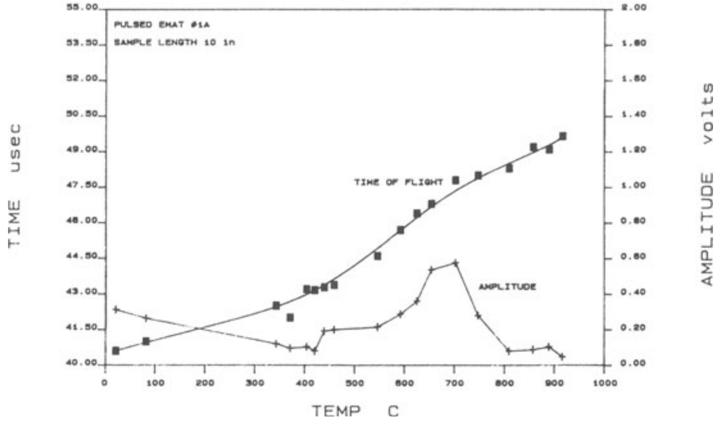


Fig. 7. Time-of-flight and amplitude versus temperature for 1008 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

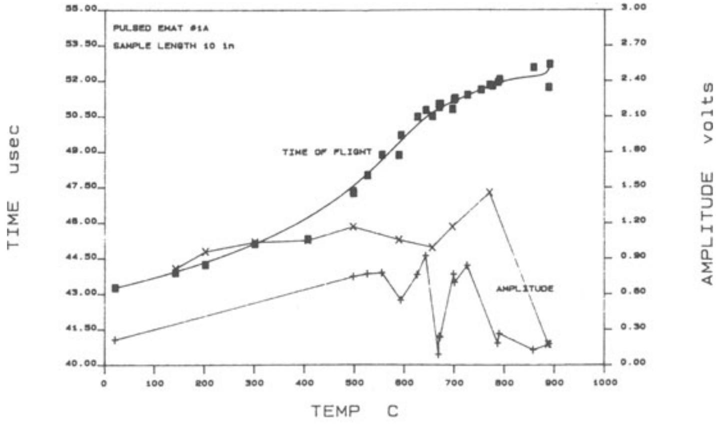


Fig. 8. Time-of-flight and amplitude versus temperature for 1018 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

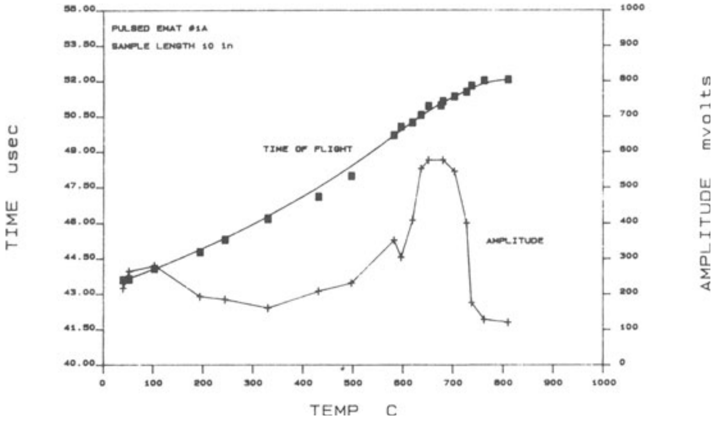


Fig. 9. Time-of-flight and amplitude versus temperature for 4130 carbon steel using a high-temperature pulsed EMAT receiver and a pulsed laser transmitter.

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.

ACKNOWLEDGMENTS

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