PROGRESS IN DEVELOPMENT OF ULTRASONIC SENSORS
FOR MONITORING HOT STEEL PRODUCT

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ABSTRACT

A steel sensor program was initiated at the National Bureau of Standards in mid-1983 by AISI and NBS. The objective of the program is to develop and evaluate ultrasonic sensors to meet two high-priority sensor needs of the steel industry: (1) detecting pipe and gross porosity in hot steel blooms, billets, or slabs and (2) profiling the internal temperature of hot or solidifying bodies of steel. Research associates from AISI member steel companies are working closely with NBS personnel in this research. Ultrasonic transducers being considered for both sensors include noncontact types such as high-power pulsed lasers and electromagnetic acoustic transducers (EMATs), as well as contact types such as PZT, using stainless steel buffer rods and molten glass as a high temperature couplant. Tomographic reconstruction of ultrasonic velocity images in a steel body is being investigated as a means of determining its internal temperature distribution. Technical challenges in development of the sensors and results to date are briefly described.

INTRODUCTION

In 1983, the National Bureau of Standards (NBS) and the American Iron and Steel Institute (AISI) established a joint program to develop process control sensors for the steel industry. The impetus for this program arose from a workshop sponsored by AISI and NBS in 1982 to review the detailed requirements of four high-priority sensors identified by the steel industry [1]. Two sensors were chosen for development under the joint program: (1) a pipe/porosity sensor and (2) a sensor to measure the internal temperature of hot steel. Most of the work under the joint program has been carried out at NBS with the participation of a number of part-time research associates contributed by several steel companies.

In this paper, an overview of the basic principles of the two sensors is first presented, followed by a discussion of the technical challenges involved in their development. Finally, a review of progress achieved to date under the joint program is given.

BASIC PRINCIPLES

Both sensors rely on the use of ultrasonic waves to probe the steel body. In the case of the pipe/porosity measurement, an ultrasonic pulse is reflected off the impedance discontinuities caused by the presence of the pipe and/ or porosity, and the reflected energy is detected. By measuring the amplitude and time-of-arrival of the reflected pulse, one may in principle determine the location, shape, and other characteristics of the discontinuities.

In the case of the temperature sensor, an ultrasonic pulse is propagated through the steel and its time-of-flight measured. From a knowledge of the distance between the transmit and receive transducers, one can calculate the average velocity of the ultrasonic wave as it traverses the path connecting the two transducers. By making many such measurements along intersecting paths, one may employ the well-known techniques of computerized tomography to reconstruct the ultrasonic velocity in steel. Combining this information with a measurement of the velocity-temperature dependence for the type of steel under investigation, then yields a temperature map of the steel body.

TECHNICAL CHALLENGES

There are a number of technical problems involved in developing these sensors, particularly in regard to high-temperature transducer technology and reconstruction of internal temperature distributions from velocity measurements.

High-Temperature Transducer Technology

Common to both sensors is the requirement for high temperature transducers to couple energy in and out of the steel body. In addition, the transducers must be able to operate in the harsh environment of a steel mill and to inspect moving product through irregular surfaces which are covered with scale, thus making poor acoustic contact with the underlying steel.

Conventional ultrasonic transducers employ a piezoelectrical material, such as the ceramic PZT-5A, to transmit and receive the ultrasonic energy. At temperatures above its Curie point (~ 290°C for PZT-5A), the piezoelectric material becomes depolarized and ceases to be piezoelectric. Thus, it cannot be placed in direct...
contact with a hot steel surface. In principle, one may separate the transducer from the steel surface by using a buffer rod which transmits ultrasound well but is a poor heat conductor. However, another problem then presents itself—that of acoustically coupling the rod to the steel surface. Previous workers have taken advantage of the ductility of steel at high temperatures to use high pressure to establish good contact between the buffer rod and steel surface. The high pressure also compresses the steel oxide (scale), thus eliminating the air spaces between the scale and steel body and further improving the ultrasonic transmission. The rolling transducer wheel based on this concept is now under development by Don Yuhua and coworkers at Magnaflex (Chicago, IL) and has been successfully demonstrated in a laboratory setup. However, there remains the concern that mechanical reliability problems may arise in scanning a steel surface with such a device in a plant environment.

First, other transducers proposed for high-temperature ultrasonic inspection involve noncontact methods and thus offer potentially better reliability. These include electromagnetic acoustic transducers (EMATs) based on the Lorentz effect (for use in both transmit and receive applications), laser interferometry for detecting the surface deflections caused by the ultrasonic waves, and laser generation of ultrasonic produced by ablation of the steel surface.

EMATs consist basically of a flat coil and magnet. They suffer from a number of disadvantages, particularly their being about a factor of 10 to 100 less sensitive than PZTs. They are also bulky and heavy, because of the need of a large magnet with appropriate cooling and thermal shielding. Furthermore, considerable development is required to increase their operating temperatures to those required in typical sensor applications in steel plants. On the other hand, apart from the advantage of being noncontact devices, EMATs are relatively unaffected by surface scale.

The laser interferometer receiver is even less sensitive than EMATs, even when used to inspect ideal surfaces which are flat, mirror-like, and stationary. Additional sensitivity losses of several orders of magnitude can be expected for the rough, irregular, scale-covered, and moving surfaces encountered in a steel plant. Furthermore, an interferometer is a very delicate device and must be protected from the harsh plant environment. Given the pressing need for sensors, the long term research necessary to determine the feasibility of this remote detection scheme is probably better left to a later stage of the program.

High-power lasers are very effective in producing considerable ultrasonic energy by ablating the surface of the steel. However, they are quite expensive and require eye protection of plant personnel. Like the interferometer, they must also be isolated from the environment of the steel plant.

Temperature Measurement from Velocity Reconstructions

Two of the principal problems involved in ultrasonic temperature measurement are the need to obtain highly-accurate measures of both the distance between the transmitters and receivers of the ultrasonic pulse. Because computerized tomography is a mathematical inversion procedure, the accuracy required for these measurements is much greater than that required for the final velocity values. Using conventional tomographic techniques, accuracies better than 0.1% would be required to approach the goals for velocity resolution set by the steel industry following the 1982 workshop. This would be very difficult to achieve, particularly in a plant environment. Accurate time-of-flight measurements are hampered by the presence of large scattering losses in steel at high temperatures and in coarse-grained material, which selectively reduce the high-frequency components in the ultrasonic pulse. The decreased sensitivity exhibited by most of the candidate high-temperature transducers decreases the signal-to-noise ratio of the received ultrasonic pulse, thus further complicating the process of determining its arrival time. Distance measurements may also be difficult to make to high accuracy because of irregularities and presence of scale on the steel surface and difficulties in accessing both sides of a steel body in practical applications.

Conventional tomographic techniques require a minimum of N independent measurements of intersecting ray paths in order to reconstruct an image of N pixels. Typically, several times this number of measurements are made in order to improve image quality. For spatial resolutions of the order of 1 cm (the ultimate industry goal), a very large number of measurements would be required to reconstruct large objects. In plant applications, this requirement may present formidable problems. Very rapid scanning must be carried out so that the temperature doesn’t change appreciably between the beginning and end of the measurement period. If the steel is in motion, even more rapid scanning would be necessary. Another potential problem is the requirement for intersecting ray paths, since not all of the possible high-temperature transducers readily lend themselves to launching ultrasonic waves at different angles.

THE NBS/AISI PROGRAM

The NBS/AISI program on pipe/porosity and internal temperature sensors has been directed initially at meeting the two technical challenges posed in the previous section. Although required for both sensors, the development of a
suitable high-temperature transducer is expected to yield immediate practical dividends in pipe/poreosity detection. This is because the availability of such a transducer would overcome the only major hurdle to immediately implementing pipe/poreosity sensing in a steel plant environment.

**Transducer Development**

A PZT/buffer rod transducer employing a liquid glass couplant was developed to avoid high-pressure coupling of the rod to the steel surface. Excellent coupling efficiency was obtained with both fused silica and stainless steel buffer rods at temperatures exceeding the melting point of the couplant (–750 °C). Use of a single buffer rod in a pulse-echo mode produced spurious signals, presumably due to longitudinal-shear wave conversion, which interfered with the reflection from the flaw. A "pitch-catch" geometry, involving separate transmit and receive transducers, was then implemented and provided excellent flaw signals. Further experiments are underway to determine the optimum couplant materials, rod material and geometry, and scanning technique. Results of this work will be transferred to Argonne National Laboratory where a large-scale test bed facility is being developed.

A major effort is being made to develop noncontact transducers. This would eliminate the surface contamination produced by the liquid glass and may also improve on the potential scanning speed of a rolling contact scanning wheel. Ablation of the steel surface with an 850 mJ Nd:YAG laser was found to generate very strong ultrasonic waves. Because it is truly remote, the laser technique lends itself to very rapid scanning of objects with even complex shape. If considerations of cost, personnel safety, and environmental effects could be satisfactorily resolved, a laser would be the ideal candidate for generation of ultrasonic pulses at hot steel surfaces.

Even if this were the case, however, one would still be left with the problem of detecting the ultrasonic waves generated by the laser. After consideration of both the optical interferometer and EMAT for the role of a non-contact ultrasonic receiver, the EMAT was chosen as the device most likely in the short term to provide adequate sensitivity for inspection of hot steel surfaces and to withstand the harsh environment of a steel plant. Also, it has the advantage of being able to function in both transmit and receive modes.

Although in principle a noncontact device, the EMAT suffers severe losses in sensitivity as it is moved away from the steel surface. On the other hand, the closer the EMAT is to the hot product, the greater the degree of thermal protection required. A distance of several millimeters appears to yield a reasonable tradeoff of sensitivity for high-temperature survivability. Even at this separation of the coil from the steel surface, substantial thermal shielding and cooling of both the coil and magnet is required and precautions must be taken in scanning the transducer over a nonflat surface. The development of such high-temperature EMATs is nontrivial, although under the direction of G. Alers, in a program funded by NBS. Another high-temperature EMAT, capable of operation to 800 °F and developed by B. Maxfield of MEA, was purchased and recently employed in our laboratory experiments on internal temperature sensing. Good sensitivity was obtained when the EMAT was coupled to a laser/ultrasound transmitter. However, additional improvements in sensitivity may be required when it is used in both transmit and receive, and/or for pipe/poreosity applications, since signals reflected from discontinuities are much lower in amplitude than transmitted signals. Furthermore, the high-temperature EMAT prototypes currently available are not able to operate at temperatures sufficiently high to meet the practical needs of the steel industry.

**Temperature Profiling**

A new reconstruction technique for bodies of rectangular cross section was developed which (1) reduces drastically the number of measurements necessary to determine the temperature distribution, (2) alleviates the severe accuracy requirements for the time-of-flight and distance measurements, (3) allows time-of-flight measurements to be made along parallel paths, and (4) allows rapid calculation of the temperature distribution. Two assumptions about the steel body were made in the analysis: the heat transfer coefficient is spatially uniform along each face, and the ambient temperature is spatially uniform along all the faces. Under these conditions, which are often approximated in practice, the two-dimensional temperature distribution T(x,y) that exists on a cross section with a square boundary factors into the product of two one-dimensional solutions, i.e., T(x,y) = f(x)f(y). (The results can also be generalized to rectangular cross sections.) This is an important simplification, since it implies that a single set of ultrasonic time-of-flight measurements over parallel paths (i.e., one "projection") is sufficient to recover the unknown function f(x), and hence T(x,y). This should be contrasted with the far more difficult problem of reconstructing an arbitrary function T(x,y), in which case hundreds of projections measured at small angular increments over 180 degrees are required to topographically recover T(x,y). Computer heat flow modeling and simulated reconstructions have shown that the assumption of factorability of the two-dimensional temperature distribution significantly simplifies the experimental complexity, accuracy requirements, and computational burden of the tomography problem.

Experiments are now underway to examine the feasibility of this approach. A steel specimen
6 inches square and 15 inches high is being examined using laser-generated ultrasound and EMAT detection. Thermocouples inserted in walls in the specimen provide an actual temperature profile for comparison with the results of time-of-flight tomography. In parallel with this effort, a multichannel computer-controlled device is being constructed with the goal of achieving the measurement speeds and accuracies that may be required in a practical internal temperature sensor.

A program is also underway to measure to high accuracy the longitudinal wave velocity in different types of steel as a function of temperature. This information is needed to convert velocity profiles into temperature profiles. Measurements to date have been made up to 1100 °C on 304 stainless and 1018 low carbon steel.

CONCLUSION

Recent experimental and theoretical work under the joint NBS/AISI program has demonstrated the feasibility in a laboratory environment of detecting pipe/porosity and reconstructing internal temperature in hot steel. Further development of both these sensors is required before they may be implemented in steel plant applications.

REFERENCE