A PULSED LASER/ELECTROMAGNETIC ACOUSTIC TRANSDUCER APPROACH TO ULTRASONIC SENSOR NEEDS FOR STEEL PROCESSING

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INTRODUCTION

Many of the traditional NDE techniques of the past are today being investigated for their potential role as process control sensors for materials processing [1]. Ultrasonics appears one of the most promising because of its ability to penetrate opaque bodies and allow determination of microstructure variables (such as grain size), process variables (such as internal temperature distribution) and detect internal discontinuities (cracks, pores and inclusions). A key problem with the traditional approaches to ultrasonic measurements is the need to contact the body being probed with piezoelectric transducers. These transducers are fragile, require couplants, and fail when exposed to temperatures of more than a few hundred degrees Celsius. Their use during processing may thus require practices that unacceptably interfere with the process.

Pulsed lasers, as a remote ultrasonic generation methodology, have been available for several years. Their use would overcome all the difficulties above if a similar remote ultrasonic receiver were available. The obvious candidate for this would be a laser interferometer, but these are of insufficient sensitivity for applications which involve unpolished, poorly reflecting surfaces. An alternative noncontact (but no longer remote) receiver could be an electromagnetic acoustic transducer (EMAT). These have the potential to be engineered to survive the process environment, and if carefully designed, to match the characteristics of a laser ultrasonic source.

This laser/EMAT approach is being evaluated as part of a collaborative American Iron and Steel Institute (AISI)/NBS sensor development program at NBS. The sensor described here is primarily needed to detect internal discontinuities within steel bodies at temperatures up to 1200°C but numerous other uses could be envisaged including time-of-flight tomography for determining internal temperature distribution.

LASER GENERATED ULTRASOUND

The generation and subsequent propagation of ultrasound by the absorption of an intense laser pulse is now a relatively well understood process [2]. Research at Hull University and Harwell in England during the early 1980's indicated that two modes of laser generated ultrasound may occur. For low absorbed fluxes, the surface where absorption occurs never exceeds its melting temperature and the source of ultrasound is then a transient dilatation. The stresses associated with this dilatation are for the most part below the elastic limit, and this mode of generation is therefore referred to as thermoelastic. At higher fluxes, the surface temperature rise is capable of exceeding the vaporization temperature. Atoms leave the surface at high velocity imparting a momentum to the substrate which is the source of ultrasound. This mode of generation is referred to as ablation.

It is possible to model the thermoelastic source using heat flow theory. For simple bodies such as isotropic elastic half-spaces and infinite plates, this theoretical description of the source can be coupled with the bodies dynamic elastic Green's tensor to quantitatively predict the temporal waveform of the ultrasonic signal [2,3,4]. The displacement signals at epicenter and various locations on the plate surface are shown in ref. 3. The response of an EMAT is proportional to surface velocity and so the velocity at the longitudinal arrival at epicenter is a positive pulse whose half width is approximately that of the source duration (in the absence of grain scattering/absorption) whilst at the shear arrival it is a negative pulse.

The ablative source is not so amenable to quantitative modelling because we do not know the mass or velocity of material ablated, or how this varies with time during optical absorption. However, if it is assumed that the source is mechanically equivalent to a momentum of arbitrary strength, temporal waveforms of arbitrary amplitude may then readily be evaluated [2]. The principle difference, as seen by an EMAT, to a thermoelastic source is that the epicenter longitudinal arrival is now a bipolar pulse with an initially negative direction. For this source, the epicenter shear arrival remains a unipolar pulse but of opposite sign to that of the thermoelastic source.

In practice, it is not possible to produce pure ablation without accompanying thermoelastic contributions to the source. The relative contributions of each to the emitted ultrasound is yet to be fully resolved, and will vary with optical flux. However, the interesting possibility exists of identifying a range where only longitudinal waves propagate because of cancellation of the shear components due to thermoelastic and ablative sources.

The displacement amplitude of a laser generated ultrasonic signal is proportional to the absorbed optical energy in the thermoelastic region. Thus, the velocity amplitude will be proportional to the absorbed optical power. This should be maximized if we wish to maximize the EMAT signal:noise ratio. At NBS, a Q-switched Nd:YAG laser is available with a 25 ns pulse duration and variable energy per pulse up to 800 mJ (average power of 32 MW). 175 mJ, 1 mm diameter pulses were used for the results reported here.

EMAT ULTRASONIC RECEIVERS

Although the EMAT is technically a noncontact ultrasonic transducer, it must be held close to the surface before the electromagnetic induction process can operate with a useful efficiency. For application to inspections of hot steel, any small air gap at the surface of the metal acts as a good thermal insulator and greatly reduces the heat transfer into the transducer structure. In addition to being physically capable of operating in a high temperature environment, the EMAT has several other features that can be exploited to advantage. By simply changing the direction of the magnetic field used, the transducer can be made to detect either longitudinal or shear waves. Also, by choosing the shape of the coil of wire inside the EMAT, the angle of incidence of the waves to which it is sensitive can be controlled. Since the electromagnetic induction process can be made to operate over a wide range of frequencies, EMATs are fundamentally broadband devices. Their frequency of operation is usually set by the electronic receiver circuits used to amplify the electrical signals. For hot steel, the best frequency of operation is determined primarily by the laser source spectrum, the ultrasonic attenuation properties of the steel and only secondarily by the structure of the EMAT and its associated electronic circuits.

An important problem to be overcome when designing an EMAT for operation on hot steel is to be sure that the electrical resistivity of the hot steel is not so high that the electromagnetic skin depth becomes comparable with the wavelength of the ultrasonic waves involved. For ordinary metals with resistivities near 10 μohm-cm, this criterion is easily satisfied for frequencies less than 10 MHz. However, hot steel has a resistivity between 100 and 200 μohm-cm so the frequency response may be attenuated above 1 MHz for longitudinal waves and 0.3 MHz for shear waves.

EMAT DESIGN

Since an EMAT consists of a coil of wire held close to the surface of the part being inspected plus a large magnetic field to flood the region around the coil, two problems must be addressed to enable hot steel bodies to be interrogated. First, the coil must be constructed with high melting point wires and a layer of thermal insulation between the coil and the steel. Second, the magnet must be designed for supplying a large magnetic field to the total area of the EMAT coil and it must be protected from the heat generated by the hot steel.

The most direct approach to supplying a magnetic field to the EMAT coil is to use a large electromagnet with pole pieces designed to concentrate the magnetic flux at the EMAT coils as shown in Figure 1(a). Here, the EMAT coils can be located in either a normal or tangential field direction and hence receive either longitudinal or shear waves. (Position A in a tangential field is suitable for longitudinal waves while Position B, in a normal field, is suitable for shear waves.) Such an electromagnet was constructed but it proved to be quite massive and difficult to move in a scanning apparatus even though it generated magnetic fields in the 4 to 5 koe range at an EMAT coil with a 1/2 inch diameter. Figures 1(b) and (c) show magnet configurations based on samarium cobalt permanent magnets located very close to the EMAT coil itself in order to maximize the fields at the coil wires. Both of these structures were assembled out of 1/4 inch thick by 1/2 inch square slabs of SmCo and fields in the range of 3 to 4 koe were measured at the EMAT coil positions. These permanent magnet structures were quite light and manueverable and thus could be easily scanned over large areas. Their reduction in efficiency caused by slightly smaller magnetic fields could be tolerated in exchange for this simplification in mechanical structure.

The EMAT coils were made thermally stable by housing their copper wires in small (1/16" diameter), four-hole ceramic thermocouple tubes.

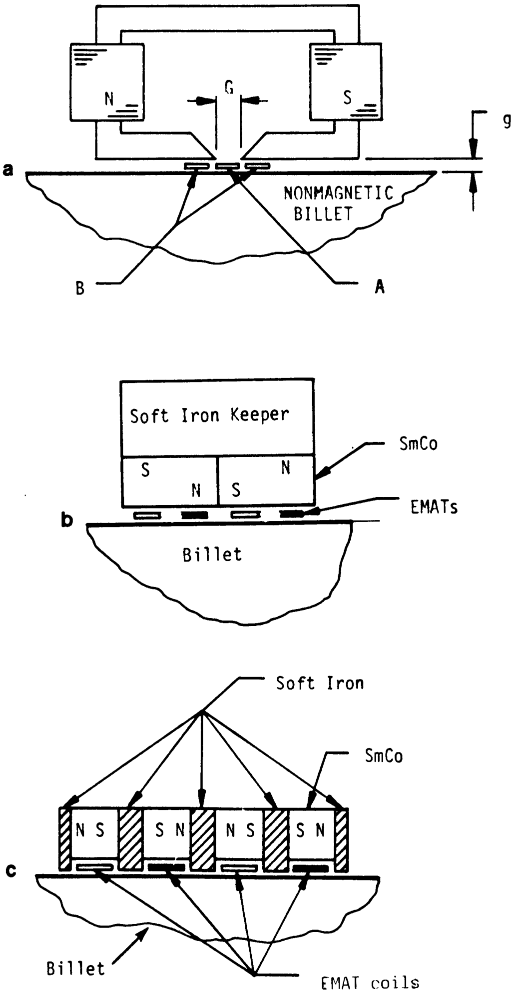

Fig. 1. Magnet configuration needed to operate EMATs. (a) Electromagnet for exciting or detecting either longitudinal or shear waves. (b) Permanent magnet arrangement for exciting or detecting shear waves. (c) Permanent magnet design for excitation or detection of longitudinal waves.

Since the duration of the exposure to high temperature was intended to be short in order to protect the permanent magnets, it was deemed unnecessary to use more expensive, high resistance wires such as platinum for the EMAT coils. By using thermocouple tubes with 1/16 inch diameters, the minimum lift-off or separation between the EMAT coil and the sample was 1/32 inch (0.8 mm). In the regions at the ends of the thermocouple tubes where the copper wires were unprotected, the wires were coated with a high temperature ceramic cement that served to thermally and electrically insulate each wire from its surroundings.

Since it was of interest to make time-of-flight measurements and because the attenuation of high frequency shear waves in hot steel is higher than longitudinal waves [5], the high temperature EMAT designed to detect longitudinal waves propagating directly through the thickness dimension of the steel samples received the most attention. Thus, the comb magnet construction technique shown in Figure 1(c), was used in all the experiments reported here. All the wires in each section of the EMAT coil between the pole pieces conducted current in the same direction but this direction reversed in the adjacent pole piece gap where the magnetic field was also in the opposite direction. In this way, the entire face of the EMAT would respond in phase to a plane longitudinal wave striking the face along its normal direction. This method of assembling the permanent magnet structure allows the pole pieces to conduct heat directly to the samarium cobalt. Thus, the ability of the probe to operate on hot objects depended critically on the length of time it took to heat the permanent magnets to a temperature at which their performance was jeopardized. The manufacturer of the magnets used in these EMATs set the upper temperature limit for his product at 330°C for continuous operation. During the tests on hot steel blocks, a thermocouple on the samarium cobalt showed that it required over 1-1/2 minutes for the temperature of the magnets to exceed 250°C. This 90 second time interval was ample time for collecting all the necessary ultrasonic information. Therefore, it was not necessary to add cumbersome water cooling apparatus at this stage.

RESULTS

In accord with the ablative mechanism of generating ultrasonic waves, very large ultrasonic signals were observed with the longitudinal wave EMAT shown in Figure 1(c) when it was positioned on the face of a sample directly opposite to the point at which the laser beam struck the sample. When a shear wave sensitive EMAT was used (Figure 1(b)), shear waves were detected only when the EMAT was displaced from epicenter along the back side of the sample. As expected from EMAT theory [6], shear waves at an angle of 30 degrees relative to the surface normal were easily detected. One surprising result was the observation of a second large shear wave signal leaving the surface of optical impact at an angle of 60 degrees relative to the surface normal. This may be a manifestation of the thermoelastic contribution to the source.

A very important performance characteristic of the longitudinal wave EMAT used here was the amount of air gap or lift-off that could be tolerated between the sample and the front face of the EMAT. Figure 2 shows how the output signal from the EMAT decreased as a function of this separation distance. This graph shows that the addition of up to 0.02 inches of thermally insulating material between the pole pieces and the hot object would not cause a significant reduction in sensitivitiy but would probably make a dramatic improvement in the ability of the structure to withstand exposure to high temperatures. The fact that the drop in signal strength is described by an exponential function is consistent with the periodic structure of this form of magnet. The rate of drop could be decreased (to achieve higher sensitivity at large air gaps) by using thicker permanent magnets to increase the separation distance between pole pieces.

A second important performance characteristic of the longitudinal wave EMAT used here was the frequency bandwidth that could be achieved with that specific EMAT design and amplifier circuit. Figure 3 shows the waveforms observed when the longitudinal wave EMAT shown in Figure 1(c)

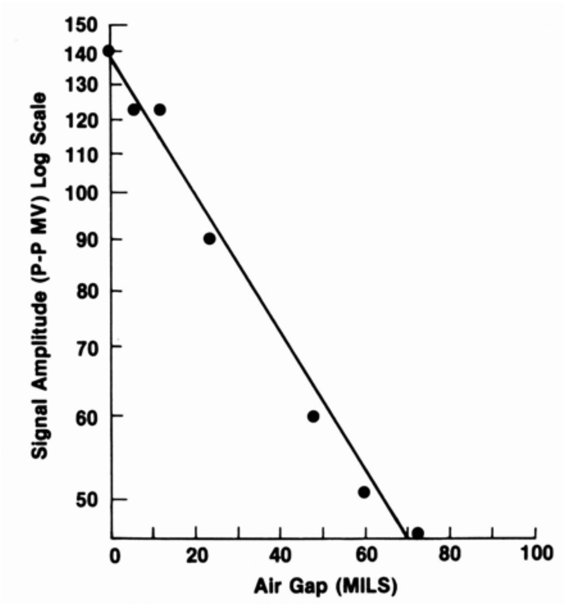

Fig. 2. Dependence of the EMAT receiver probe sensitivity on the thickness of the air gap between the probe and the surface of the sample.

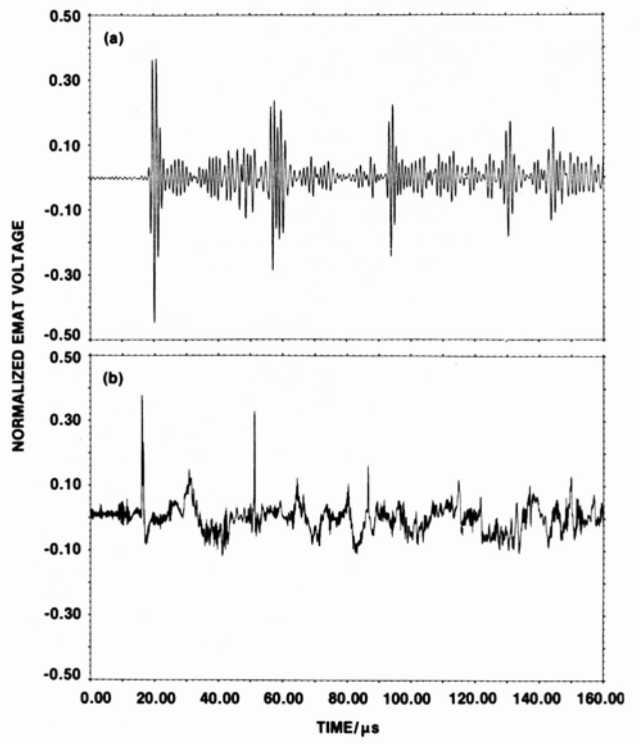

Fig. 3. Ultrasonic longitudinal waveforms observed with different electronic tuning circuits connected to the EMAT coil. (a) Band pass filter combined with a tuning capacitor across the EMAT coil. (b) No tuning.

was used to receive directly transmitted longitudinal waves generated by the pulsed laser. When narrow band filters were used in the amplifier stages, the waveform shown in Figure 3(a) was observed. Note that the noise received prior to the ultrasonic wave arrival is very small and the electrical signal is a tone burst containing many cycles of oscillation. Figure 3(b) shows the effect of removing all the filters and tuning capacitors from across the EMAT coils to achieve a large bandwidth. The noise level prior to the arrival of the acoustic wave is much higher than in the previous cases. However, it appears that the arrival time could be measured to an accuracy greater than 0.1 μsec (or 0.6%).

In order to demonstrate laser excitation and EMAT reception of ultrasonic waves in hot steel, two large steel block samples were heated in a large furnace at 980°C (1800°F). One sample was made of 304 stainless steel and hence underwent no ferromagnetic transition as it cooled off. This sample was a 4-inch diameter cylinder in which the sound wave propagated along the 4-inch long axis of the cylinder. The second sample was a 6-inch by 6-inch square slab of 1018 steel arranged so that the sound wave propagated parallel to the 4-inch thickness dimension. For this sample, a transition from the nonmagnetic to magnetic state would be expected when the temperature passed through the Curie temperature of 770°C (1418°F). These hot blocks were positioned such that the focal point of the laser beam was at the center of the front surface of the sample. The EMAT was then rested lightly against the back surface directly opposite the laser impact point. Thermocouples were held against the sample surface and inserted into the EMAT structure at the location of the samarium cobalt permanent magnets in order to monitor the local temperatures while the steel cooled and the EMAT heated up.

Figure 4 shows examples of the waveforms observed on the 4-inch long, stainless steel cylinder as its surface temperature fell from 752°C to 322°C. The directly transmitted longitudinal wave signal and three reverberations can be easily distinguished from the background noise. Most of this noise is probably from ultrasonic signals reflected by the side walls because the noise is at the EMAT frequency and increases with time after the laser impact. Note that the time interval immediately following the laser pulse and prior to the arrival of the first, longitudinal wave signal is very quiet at all temperatures. As the sample became more cool, the acoustic noise between the reverberation signals increased. This may be explained by mode conversion at the side walls plus a dramatic lowering of the attenuation for shear waves formed by mode conversion as the temperature of the steel became lower.

Figure 5 shows the waveforms observed on the 4-inch thick slab of 1018 steel as the surface temperature dropped from 810°C (1490°F) through the Curie temperature to 618°C (1144°F). At the highest temperature studied, the ultrasonic longitudinal wave signals were very well defined and appear similar to the signals observed on stainless steel. Below the Curie temperature, the magnetic field from the pole pieces of the comb-type EMAT flowed directly into the steel in the immediate vicinity of the pole piece so that the tangential field at the EMAT coil became greatly reduced. Therefore, the sensitivity to longitudinal waves fell and the directly transmitted longitudinal wave which should arrive at about 20 μsec was no longer the dominant signal observed. Instead, a late arriving pair of signals appear which are probably shear waves that have reached the EMAT by reflecting from the side walls of the sample. Since these shear waves have reflected from the side of the sample, they must impinge on the EMAT at an angle and would be detected if a periodic normal magnetic field existed in the EMAT structure. Such a field is actually present in the immediate vicinity of the pole pieces of the comb-type EMAT

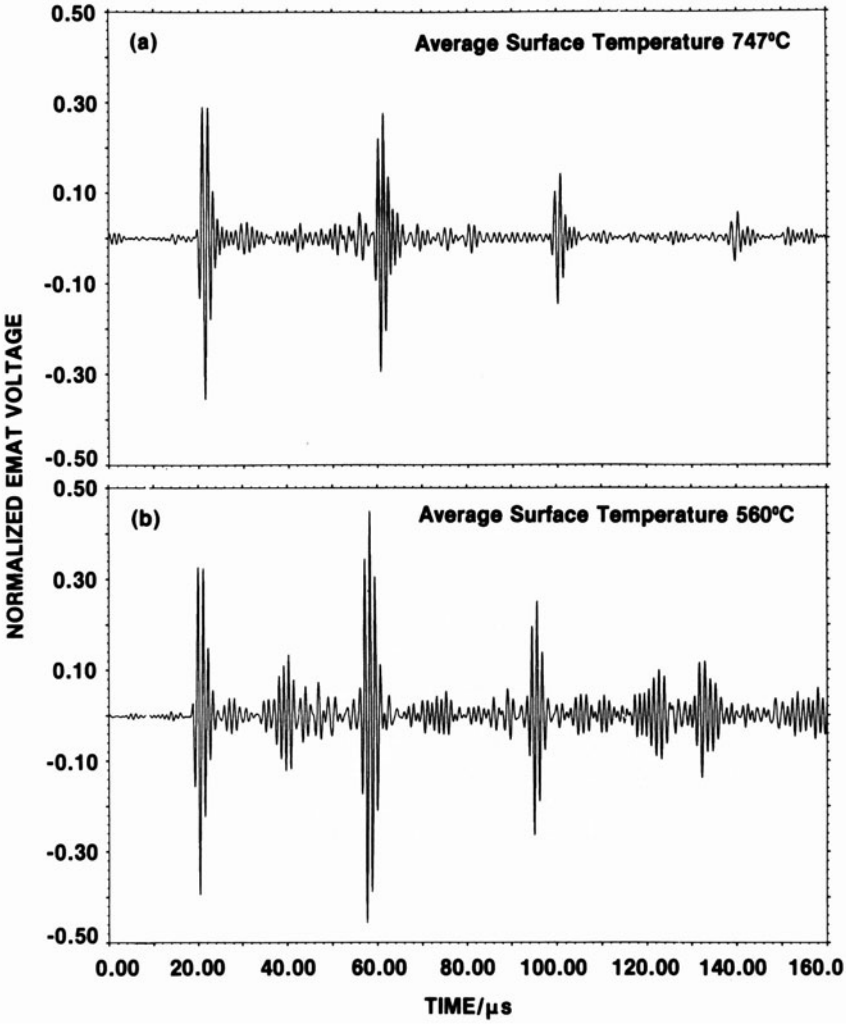

Fig. 4. Waveforms on a 4-inch thick stainless steel block.

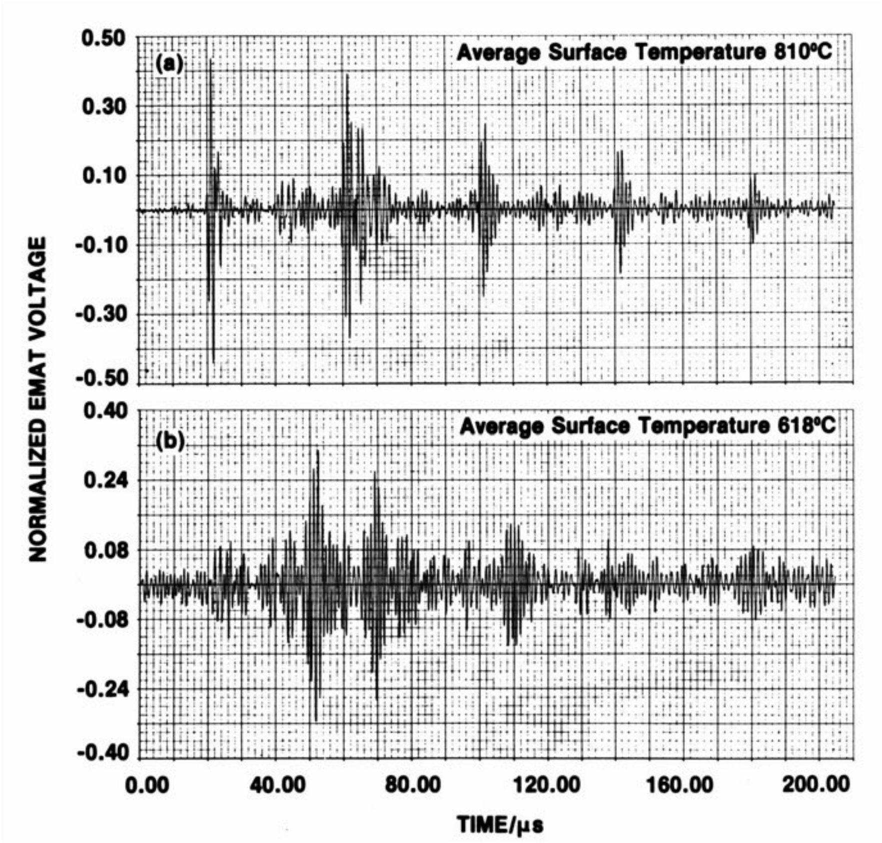

Fig. 5. Waveforms on a 4-inch thick 1018 steel block.

when it is in contact with a sample that is ferromagnetic. An analysis of the geometrical dimensions of the EMAT used in these experiments indicates that the EMAT would be sensitive to shear waves that approach the face of the probe at an angle of about 48 degrees relative to the surface normal. Such an angle is reasonably consistent with the sound wave paths reflected by the side walls of the sample.

CONCLUSIONS

1. A lightweight, easily scanned EMAT receiver probe has been constructed out of heat resistant materials and samarium cobalt permanent magnets to withstand intermittent use at high temperatures. It has been optimized for use with a pulsed laser ultrasonic source.

2. This probe was able to detect 1 MHz ultrasonic pulses generated by a focused 175 millijoule laser pulse with a signal-to-noise ratio of 40:1 (32 dB) on a mild steel block with a surface temperature of 810°C (1490°F). Similar results were also obtained on a stainless steel sample.

3. No degradation of performance was observed after the probe had been repeatedly held in contact with hot steel for time intervals that ranged from 60 to 90 seconds for each contact even though no active water cooling was employed. It now appears relatively straightforward to devise EMAT's for semi-continuous use at temperatures up to 1300°C.

ACKNOWLEDGEMENTS

The help and assistance of F. Mauer and J. Martinez is gratefully acknowledged.

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DISCUSSION

From the Floor: Have you considered using the new permanent magnet materials to achieve more efficient transducers?

Mr. Alers: Yes. The EMATs I described used samarium cobalt magnets already available in our laboratory. Much better materials with about one and a half times the energy product are not available.

From the Floor: I found that a neodymium-iron-boron alloy gave about 25 percent more field. However, this result depends on the composition and the geometry.

Dr. R. B. Thompson: The neodymium iron alloys have a much lower Curie temperature.

Mr. Alers: That's right. In any case, we may have to spray some water on the back.

Dr. C. Fortunko: I just wanted to make a few comments. One is that samarium cobalt doesn't go up to 360 degrees. I think it has a phase transition at about 200 or so degrees centigrade.

Mr. Alers: The manufacturer's literature advertises continuous operation of some samarium cobalt compositions at 350° C.

From the Floor: What are the highest frequencies that your EMAT can pick up this wave?

Mr. Alers: Well, that would have to be determined experimentally, so I can't answer your question. Personally, I doubt if we can even get 5 MHz through the steel. Therefore, I think it's academic whether the EMAT will respond to frequencies higher than 5 MHz or not.

Mr. S. Rokhlin: I understand that the thickness of your sample was roughly three inches.

Mr. Alers: A four-inch thickness.

Mr. Rokhlin: What response was obtained?

Mr. Alers: We observed perfectly good signal-to-noise ratios after three or four bounces, which would correspond to an acoustic path of more than 12 inches in this case.

Mr. Rokhlin: It was not clear how the lift-off was minimized. How were you able to fix the gap under the transducer?

Mr. Alers: The graph of signal versus lift-off indicates that the rate of decrease of signal with separation is about what would be expected for an array of magnets with about one quarter of an inch spacing between the pole pieces. This agrees with the dimensions on the inside of the EMAT used. If you made an EMAT with a half inch magnet array its signals would fall by a factor of two in 60 mils of lift off instead of the 30 mils we observed. Our experience indicates that the normal air gap under an EMAT in light rubbing contact is much, much less than these characteristic dimensions of 30 to 60 mils.

Mr. Bernie Tittmann, Rockwell Science Center: Your radiation patterns on both the transmitter and the receiver are fairly broad, so what does that say about the need to carefully align the transmitter beam with the detector beam? Maybe the problem of scanning is not nearly as severe as one might believe.

Mr. Alers: We are operating with pretty big dimensions, so alignment is not very critical. The real reason we looked into the angular dependence was there may be a lot of energy going off at some angle and we could therefore optimize the receiver for that angle and achieve sensitivity. However, one must be careful not to walk into a big trap of mode conversion and loss of the entire signal.

Mr. Sachse, Cornell: The other day, there was a talk here about a wheel with a transducer built into its center. How do your signals compare to the kind of signals that those people get?

Mr. Alers: They didn't show any pictures of their raw signals which would allow us to compare the signal-to-noise ratios obtained by the two techniques. I think we are getting comparable signal-to-noise ratios. However, they were looking at three quarter inch diameter flat bottom hole reflectors while we were just doing straight transmission. Therefore, there is still a lot to be done to compare the two techniques.