ELECTROMAGNETIC INDUCTION OF ULTRASONIC WAVES: EMAT, EMUS, EMAR

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Electromagnetic induction of ultrasonic waves is restricted to conducting materials – like eddy current testing – because it involves inducing eddy currents in the surface of the part by a near-by coil of wire. A magnetic field supplied by a near-by magnet interacts with this eddy current to produce a mechanical force on the surface to excite ultrasonic vibrations. The same configuration of coil and magnet also detects mechanical motion of the surface because the motion of a conductor in a magnetic field produces currents that are detected and measured by the near-by coil.

This transduction by induction has the following advantages for NDT: (1) The "near-by" feature implies an air gap next to the part surface and, thus, no coupling liquid or grease layer is present to restrict the range of temperatures or inspection speeds available for testing. (2) The fact that the transduction process takes place within a thin layer *at the surface of the part* allows the time-of-flight (or phase) of the ultrasonic wave to be measured with great accuracy so that dimensions and physical properties of materials can be used for quality assurance purposes. (3) The shape of the coil and the direction of the magnetic field allow the type (shear or longitudinal) and direction of propagation of the wave to be controlled by the transducer design. (4) Special wave types (e.g., shear horizontal, Lamb, Rayleigh) are readily available to satisfy unusual inspection problems. (5) Coils that are large or contoured to fit odd shapes are inexpensive and extend the range of part geometries available for inspection.

The primary disadvantage of EMATs is their inefficiency. However, this drawback has been overcome with modern electronic design and digital signal processing techniques.

Introduction: The transducers usually used for ultrasonic testing are hand-held probes that must be coupled to the object being tested by a water bath or a thin layer of grease. This latter requirement is often messy and adds considerable mechanical complexity to the test as well as challenging the skill of the operator to get reproducible results. Eliminating this coupling chore and introducing transducers that can operate across an air gap has always been a "holy grail" quest. About 40 years ago, the quest began to be fulfilled with the introduction of high power lasers and air coupling techniques that are being described in the accompanying papers. This paper describes an electromagnetic technique that operates across a small air gap similar to the gap under eddy current sensors. Thus, it is only *technically* a non-contact sensor. However, it is able to takes full advantage of the absence of a liquid coupling layer. It generates and detects ultrasonic vibrations in a *thin surface layer* of metallic objects and, therefore, is immune to small surface undulations or layers such as dirt, paint, rust, grease, etc. that prevent piezoelectric transducers from giving reliable resultsin hostile environments. The physical principles are based on the same electromagnetic induction processes that govern electric motors and generators. That is, a wire carrying an alternating current and held close to a conductor will induce eddy-currents in the conductor. If a large magnetic field also floods the area of the eddy-current, forces are generated in the conducting surface by electric motor action and these launch acoustic waves into the conductor at the same frequency as the current that drives the wire. When used as a receiver, acoustic vibrations inside the conductor move the surface under the wire. In the presence of a magnetic field, this motion produces an eddy current in the conductor surface that produces a magnetic field that extends across the air gap to induce a current in the near-by wire connected to a preamplifier.

Figure 1(a) shows a diagram of the basic structure of an electromagnetic acoustic transducer or EMAT. It consists of a magnet (either a permanent or an electromagnet) and a wire located above the metal surface and in the magnetic field. Figs. 1(b) and 1(c) are drawings of practical embodiments of this structure that might be found in practical applications of these principles. Fig. 1(b) shows the wire bent into a meander line shape. In this case, the eddy currents are periodic and flow in a uniform magnetic field. The spacing between adjacent wires makes this type of coil particularly sensitive to waves whose wave length is twice the spacing between the wires. Fig 1(c) shows the coil as a flat pancake that makes the eddy current under it follow a contour that resembles a race track.. Here, the eddy currents under the coil find themselves subjected to a periodic magnetic field. This form of periodic magnetic field and uniform eddy

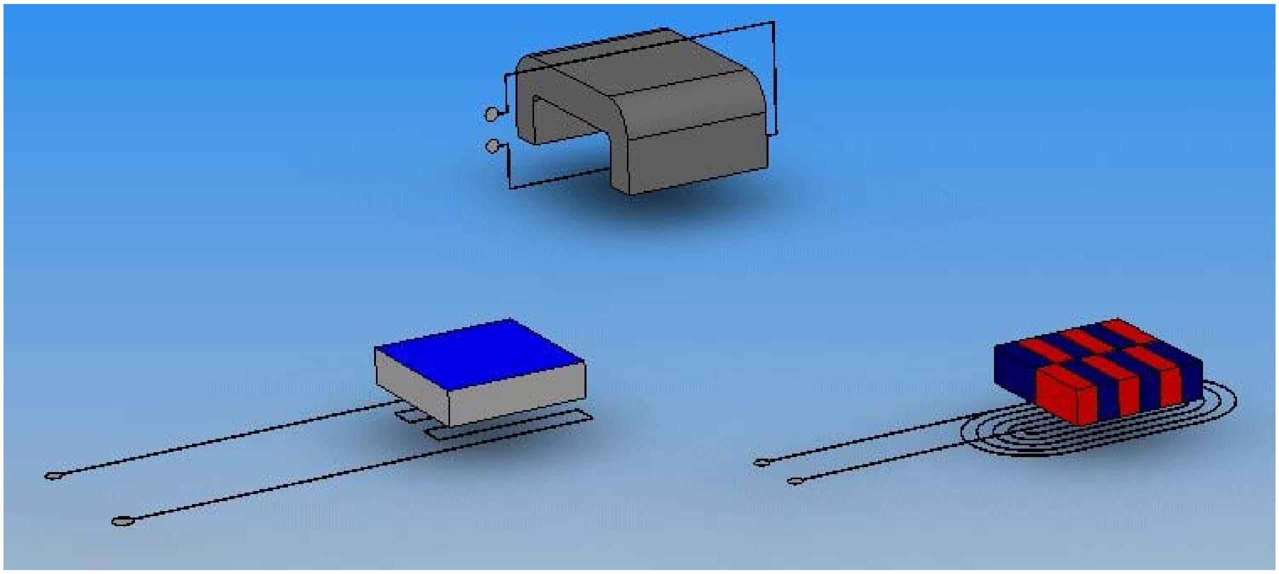

Figure 1. Construction details of an EMAT. (a) Simplified structure to show the essential parts – a wire to induce eddy currents in a conducting surface and a static magnetic field. (b) A meander line coil under a large permanent magnet pole. (c) A periodic array of magnets that apply alternating magnetic fields to an eddy current sheet flowing in a race-track pattern.

current generates or detects shear horizontal (SH) waves whose wavelengths are twice the width of the individual magnets.

These transducers operate on any conducting material and are known by the acronym EMAT (Electromagnetic Acoustic Transducer) or Electromagnetic Ultrasonic Sensor (EMUS). The acronym EMAR (Electromagnetic Acoustic Resonator) applies to the case of electromagnetic excitation or detection of resonant mechanical vibrations in an object. In magnetic materials, a separate transduction mechanism that results from magnetostriction in the material may dominate the ultrasonic wave generation and detection process to make a more efficient transducer. This type of device has been referred to as a MUT – an acronym for Magnetostrictive Ultrasonic Transducer. A detailed theoretical analysis of this class of transducer can be found in recently published books[1,2]. In these treatments, the sensitivity is often expressed by a *transfer impedance* between a transmitter and receiver pair of devices that communicate via the acoustic wave that passes between them . The transfer impedance is the voltage output at the receiver coil's terminals divided by the current being driven through the transmitter's coil. Thus, its units are ohms. Under good conditions (magnetic fields of the order of 5,000 gauss and many turns in the EMAT coils), the output voltage can be as large as a millivolt when the transmitter current is 100 amperes – a transfer impedance of 10 microhms. Achieving these levels of current in the transmitter coil and amplifying the receiver voltages with a minimum of noise requires careful electronic design procedures but it can be done with commercially available instrumentation.

Results: The following paragraphs give specific examples of the application of electromagnetic transducers to inspection problems that conventional piezoelectric transducers find difficult to solve. They have been divided into sections that exploit particular advantages of noncontact ultrasonics. Additional information can be found in review articles in technical journals[3] and books[4].

A. Ultrasonic Inspections Without a Coupling Medium:

A1. *Inspection of Buried Gas Pipelines.* Gas pipelines are, in reality, very long steel pressure vessels buried in the ground. Thus, they are subject to corrosion that can take the form of pitted areas or stress corrosion cracks – either of which can jeopardize the safety of the entire pipeline. The obvious method of inspecting the lines for such damage is with instrumented robots that can be driven along the pipeline by the flow of the gas. Conventional ultrasonic techniques that use waves propagating in a circumferential direction are well suited to detecting and sizing longitudinal stress corrosion cracks but getting the waves in and out of the pipe wall at high speed without a coupling medium has proven difficult. EMATs immediately overcome this coupling problem and can interrogate the pipe wall with Lamb waves (at low frequencies) or angle beam shear waves (at higher frequencies). The basic technology is described in the original patent 4,092,868 and early publications[5, 6]. Recent development activities with this technique have overcome the mechanical problems associated with maintaining the small air gap between the EMAT coil and the pipe wall as well as with supporting the permanent magnets that supply the required magnetic fields. Still remaining is the general problem of detecting and sizing stress corrosion cracks with ultrasonic waves.

A2. *On-line Measurement of the Wall Thickness of Seamless Steel Tubing* . Seamless tubing is manufactured by forcing a piercing tool through a billet at very high temperature. Because any wobble in the tool can produce variations in the wall thickness, it is important to monitor the thickness dimension as soon as possible after the piercing operation in order to keep thin spots out of the final product line. Conventional ultrasonic thickness gages can only spot-check the thickness after the tubing has cooled to near room temperature. By using EMAT coils fabricated from heat and wear resistant materials and small pulsed electromagnets that needed no cooling, it was possible to assemble a compact EMAT sensor probe on wheels that could be brought in contact with the pipe as it passed through an inspection station at a production mill speed of 180 ft./min (0.9 m/sec). Eight such probes distributed around the pipe's circumference produced a continuous read-out of thicknesses along eight axial paths with a resolution of approximately 1/8" (3 mm) between readings. Computer based signal processing and display software presented the mill operator with a thickness vs position map of the pipe joint within seconds after the pipe had passed through the inspection station. Any data points that exceeded preset limits for the thickness dimension set off an alarm system and directed the pipe to an off-line location for manual verification of the results found by the EMAT system. More details on the operation of this system can be found in elsewhere[4].

A3. *Monitoring of the Billet Temperature During Continuous Casting of Steel.*_Continuous casting of steel is accomplished in modern steel mills by allowing the molten metal to flow from the furnace through a cooled tube onto a bed of rollers. A solid layer of steel is formed at the tube-to-steel interface and this acts as a mold for the hot metal as it emerges from the tube. Inside this "mold", the steel remains molten for a considerable time and it is very important to monitor the location of the liquid-solid interface to prevent a break-out of the liquid from the "mold". Because of the discontinuity in acoustic impedance at the liquid-solid interface, it is not difficult to measure the thickness of the solid layer with an ultrasonic thickness gage *if the gage can withstand surface temperatures approaching 1200 C.* A ceramic encased EMAT coil and magnet similar to that described in US Patent 4,777,824 was assembled and demonstrated in a continuous casting mill in 1988[7,8].

A4. *Dry Inspection of Automotive Air Bag Inflators.* Universal installation of air bags in automobiles has produced a need for mass production of small pyrotechnic devices to inflate the air bag during a collision. In some designs, mating parts of the inflator device must be welded together in a dry environment to avoid contaminating the pyrotechnic chemicals. Subsequent inspection of the weld by ultrasonic techniques must also be performed without contact with water. Thus, EMAT techniques are required. Special EMAT coils shaped to match the contour of the welded joint were placed under small permanent magnets to generate and detect bulk shear waves that propagated normal to the welded joint surface. In this configuration, the joint was inspected by conventional pulse-echo signal processing techniques. A secondary advantage derived from the use of couplant-free EMATs was that the parts could be moved rapidly past the EMAT to yield a high throughput of 100% inspected parts.

A5. *Rapid_Inspection of Mass Produced Parts with Irregular Shapes.* In the production of munitions, hollow projectiles with an ogive nose, grooved sides and a flat bottom must be inspected for cracks and internal defects that could cause premature detonation during manufacture or during firing from a gun on the battlefield. Angle beam shear wave inspection of the projectile walls with an array of conventional piezoelectric transducers deployed around the ID and OD surfaces requires immersion of the projectile in a water bath and precision alignment of each and every transducer in a jig of considerable mechanical complexity. By using meander wound EMAT coils pressed lightly against the surface and by placing the entire projectile in a general magnetic field, angle beam shear waves were directed around the circumference and into the interior corners where cracking could have serious consequences. Thus, the need for precision jigs to support the transducers were eliminated and the expense of a large array of individual piezoelectric elements was replaced by a collection of less expensive meander coils. Furthermore, the assembly line for the projectiles did not have to include special drying stations because the inspection was performed on dry surfaces. Additional information on this particular ultrasonic inspection method can be found in the US patent 4,184,374 entitled "Ultrasonic Inspection of a Cylindrical Object".

A6. *Inspection of Electron Beam Welds Inside a Vacuum Chamber.* Gas turbine engine parts made with very special alloys often need to be welded by electron beam or laser techniques under vacuum conditions to avoid contamination of the weld by an atmosphere. Conventional ultrasonic inspection of the completed weld required removal of the part from the vacuum chamber, immersing it in a water bath and scanning it with careful aligned piezoelectric transducer probes. By using high frequency meander coils curved to focus the ultrasonic wave fronts into the weld line, an angle beam shear wave inspection was performed by the pulse-echo technique using EMATs. Since the magnetic field required by the EMATs would disturb the electron beam, the ultrasonic inspection was performed after moving the part in the vacuum chamber away from the welding position to a near-by station where it could be rotated past a fixed EMAT probe. This probe used a pulsed electromagnet for its magnetic field in order to minimize any retained magnetization in the part if it had to be moved back to the electron beam for a repair weld. In the production line version of this inspection system, four individual parts could be welded and inspected with one pump-down of the chamber. By using focusing meander coils at 7 MHz, a C-scan of the weld line was able to display a 0.03" (0.75 mm) diameter flat bottom hole as a circle with 0.004" (0.1 mm) pixel resolution. Additional information on the use of EMAT generated angle-beam shear waves for weld inspection can be found in ref. 9

B. Flaw Detection by Special Wave Modes in Plates, Pipes and Bars.

B1. *Rayleigh or Surface Waves*. Piezoelectric transducers can be made to excite and detect surface waves by coupling a piezoelectric material to a wedge shaped block so that the ultrasonic wave in the block will strike the surface of the material to be studied at an angle set by Snell's Law. The frequency of operation of the device is set by the thickness of the piezoelectric material and the wave length is set by the (fixed) angle of the wedge. For an EMAT, the wave length is fixed by the spacing of the wires in the meander coil and the frequency can be whatever value equals the ratio of the Rayleigh wave velocity in the material to be studied to twice the wire spacing of the meander coil. Thus, the same transducer unit can be used on any material by simply making an appropriate adjustment to the frequency of operation. An excellent example of the power of surface wave EMAT technology is the application to on-line inspection of bar products at the mill site[10]. Here the surface waves are directed in a circumferential direction around the bar as it moves at production line speeds and temperatures through the bar mill. Since no coupling medium has to be maintained under the meander coil, a measure of the amplitude of the waves after each trip around the bar can be used to determine the apparent surface wave attenuation of the ultrasonic surface wave on the bar surface. This quantity is determined by the beam spread, the microstructure of the material and by scattering from any defects in the surface. For longitudinal laps and seams, the scattered amplitude and hence the attenuation can be shown to be a universal function of the wave length of the surface wave to the depth of the flaw[11]. Thus, by knowing the separation distance of the wires in the EMAT coil, the absolute depth of the lap or seam can be determined and the amount of material that must be ground out to remove the defect can be established.

B2. *Inspection of Pipes by Guided, Circumferential Waves.* The same meander coil EMAT designs used in the application to bars described above can be applied to pipes. Here, the circumferential waves are Lamb waves and the same relation between the frequency and wave length can be used to design the EMAT probe except the phase velocity of a particular Lamb wave mode replaces the surface wave velocity. If a periodic permanent magnet array and a race track coil replace the single magnet and meander coil described above [see Figs. 1(b) and 1(c)] the circumferential waves are SH waves with their own unique relationships between phase velocity and frequency. In any case, the amplitude of the signals that have traversed the circumference several times can be used to measure a wave attenuation value that can be related to the scattering by various flaw types and hence used to classify and size the defects. An additional feature of using of circumferential Lamb waves is to measure the time it takes for the wave to cover the circumference. This quantity is determined by the group velocity of the particular Lamb wave mode being used and is dependent on the thickness of the pipe wall. If the wave encounters a region of wall thinning caused by corrosion, the group velocity will be changed in that area and a shift in the transit time of the wave around the circumference can be measured. This time shift can then be used to determine the depth and physical extent of the corrosion. A more detailed description of this use of EMATs can be found in US Patent 5,619,423.

B3. *Ultrasonic Inspection of Piping at Pipe Supports.* Wherever long lengths of pipe are exposed to the environment, corrosion can be expected to occur. Usually visual inspection is sufficient to detect such problems but areas under pipe supports or where the pipe enters the ground or goes into a concrete vault are hidden and are natural sites for serious corrosion to develop undetected. EMATs like those described above can be rotated to put the direction of propagation in the axial direction – thus, sending the Lamb waves along the length dimension of the pipe. Thus, they can be well suited to the detection and sizing of corrosion under pipe supports. If SH wave modes are used, there is poor coupling to the pipe surroundings and the waves can propagate for considerable distances along liquid filled pipes, under coatings or soil as well as past the interface between a pipe and its support structure. If the wave length is comparable to the pipe circumference, an axial propagating SH wave will become a torsional wave of the entire pipe and very long distances can be inspected. At shorter wave lengths, the ultrasonic energy can be confined to a beam or even focused to facilitate the generation of maps of corroded areas by scanning a small aperture EMAT in the circumferential direction and monitoring the amplitude of echo signals returning from the corroded area. Theories to describe the scattering of SH waves by isolated cracks and pits in plates or large diameter pipes are being developed so that quantitative estimates of the depth of a pit or crack can be inferred from the amplitude of the reflection from these defects[12].

B5. *Long Range Inspection of Heat Exchanger Tubes.* One of the first applications of EMATs to an industrial inspection problem was for detecting circumferential cracks under the supports of long tubes in heat exchangers. Here, impurities in the water outside the tubes could collect at the supports and cause localized cracking that conventional eddy current inspection techniques would not detect because the large signal from the support masked the small signal from the crack. A periodic permanent magnet and race track coil mounted on a probe that could be inserted in the end of the tube produced an SH wave polarized in the circumferential direction and propagating in the axial direction – that is, a torsional wave mode of the tube. Because the wave was polarized parallel to the thin support plate, it could pass a support without creating a significant reflected signal and proceed around gradual bends to the end of the tube where a large reflection signal would be produced. If a circumferential crack were present at a support, the crack surface would produce a large reflection and the crack could be easily detected by simple pulse-echo signal processing. Because the torsional wave traversed the full length of the tube (70 feet or 21 meters), all of the support regions could be inspected by a single ultrasonic wave pulse launched and detected at one end of the tube. Additional information on the torsional wave EMAT can be found in US Patent 4,127,035.

B6. *Long Range Inspection of Railroad Tracks.* With the expanded use of welded rail, an interest in using acoustic waves propagating along a rail for communication and detection of broken rails has occurred. Experiments and theoretical analysis have shown that there are modes of motion of a rail that couple very little energy into the ties and roadbed[13]. That is, the acoustic energy is trapped in one part of the rail cross section such as in the head or in the web. This allows these particular modes to propagate over very large distances. By knowing the surface displacement distribution of these modes, an EMAT can be designed to preferentially excite or detect that particular mode – thus increasing the acoustic energy that can be put into the mode at a transmitter and reducing the noise from other vibrations at a receiver EMAT. Some EMATs that embody these design principles have been constructed and tested on operating railroad tracks and communication over distances exceeding a half mile have been observed[14].

B7. *Ultrasonic Inspection of Wire Cables with Guided Waves.* Wire cables are critical to many industrial applications and are difficult to inspect with nondestructive techniques because of their heterogeneous internal structure. Ultrasonic inspection is particularly difficult because the high frequencies usually used excite modes of motion within the individual wires. Furthermore, the irregular surface does not present much area for coupling energy out of a piezoelectric transducer into the cable. By using EMATs whose coils and magnets are designed to excite modes of motion of the entire collection of wires as if it were a bar, most of these problems can be overcome. Stated another way, the EMAT operating frequency and coil geometry can be chosen to excite acoustic waves with wave lengths that are long compared to the wires diameters so the equations for wave motion in cylinders in the long wave length limit can be used with only slight modifications for designing the EMAT. An application of these ideas to the detection of corrosion in buried copper grounding cables by torsional waves propagating over significant distances is described in US Patent 6,382,029.

B8. *Flaw Detection in Butt Welds at a Pickle Line.* Preparation of thin sheet metal for stamping operations in the steel industry requires accepting coils of thick (~ ¼") steel, etching the surface (pickling) and rolling the clean sheet to a thickness suitable for the stamping mill (~ 30 to 60 mils). This process is most economically performed on a continuous "ribbon" of metal. Therefore, the end of one coil must be butt-welded to the beginning of the next roll and the weld must be strong enough to survive the entire rolling and finishing process. Visual inspection of the weld-line at the machine that automatically makes the butt-weld is not always reliable and a break in the "ribbon" during subsequent operations has proven to be very expensive in damaged equipment and shut-down time. An EMAT based inspection of the butt-weld immediately after its formation in the welding machine has been described in the open literature[15] and developed into a commercial inspection system by Patents 5,474,225 and 5,537,876.

C. Ultrasonic Materials Characterization with Precision Wave Velocity Measurements.

C1. *Measurement of Texture and Predicting the Formability of Steel Sheet.* The steel industry makes extensive use of sheet metal deformed into complex shapes for the automobile industry. Experience has shown that particular rolling textures or preferred orientations of the grains in the steel will accommodate large amounts of bending before cracks form at sharp corners. These desirable textures can be detected by measuring the angular dependence of the phase velocity of certain Lamb waves in the sheet. By using EMATs to excite and detect these specific modes, their angular dependence can be measured quickly under rolling mill conditions and a prediction of the formability of a particular coil of steel sheet can be made long before any complex shapes are actually fabricated. A complete description of this use of EMAT generated Lamb waves is available in US Patent 5,154,081 and in Ref. 16

C2. *Measurement of Residual Stress* . It has been known for some time that the velocity of sound is a linear function of the stress – either applied or residual. Unfortunately, the effect is very small and can often be masked by other sources of uncertainty in the measurement. By using EMATs, errors associated with transducer coupling can be eliminated and comparisons between waves propagating in different directions can eliminate others. In particular, the difference between ultrasonic shear waves propagating through the thickness dimension of a plate with polarization directions parallel and perpendicular to the stress can measure the stress directly. This is the ultrasonic birefringence technique. Its utilization with EMATs is described in Patent 6,502,463 and in the technical literature[17]. Another purely EMAT technique utilizes the ease with which the polarization and propagation directions of an SH wave can be interchanged to expose a relative change in sound velocity that is linear in the stress and independent of any preferred orientation in the grain structure. Reports on the development of this technique can be found in the technical literature[18].

*C*3. *Measurement of Case Depth in Drive Shafts.* In order to extend the fatigue life and reduce wear in steel drive shafts for the automobile industry and elsewhere, it is common industrial practice to heat and quench the shaft to create a hard layer at the surface called a "case". The thickness of this case layer is determined by the details of the heating and quenching cycle and must be monitored to insure the reliability of the shaft for its intended use. EMATs designed to excite SH and Rayleigh waves that propagate around the circumference of the shaft can be used to measure the case depth by comparing the ultrasonic response at high and low frequencies because the high frequency waves are influenced by the properties of the surface while the low frequency waves measure the average properties of the entire shaft. In the practical implementation of this concept, the greatest accuracy and speed of inspection was obtained by employing electromagnetic resonance (EMR) techniques in which the EMAT construction method determined the specific mechanical resonance modes that were excited. These modes have been chosen to emphasize the differences between the surface and bulk properties of the shaft. Details of the EMAT construction and their application to the measurement of case depth in US Patents 5,813,280, 5,895,856 and 6,170,336.

C4. *Measurement of the Elastic Constants.* The elastic moduli, Cij, of a material are closely related to its chemical composition and microstructure. Thus, their measurement provides a very useful, and fundamental, basis for materials characterization. Many important mechanical properties such as hardness, yield strength, etc. can be correlated with elastic moduli that can be deduced from accurate sound velocity measurements on a given material. Unfortunately, the correlations show that the sound velocity must be measured with a precision of ±0.1% to be useful and conventional piezoelectric techniques are accompanied by errors larger than this that arise from the coupling layer between the transducer and the material surface. By using EMATs, these errors do not exist because the ultrasonic waves are excited and detected in the surface itself and the geometrical path can be defined very accurately. In particular, if the transmitter and receiver EMATs are mounted on a precision translation stage such that their separation can be measured to high precision, the shift in transit time of the ultrasonic wave can be measured along with the change in separation to yield a direct measurement of the phase velocity of the wave propagating between them. If the material is in the form of a plate or sheet, the propagating wave is a Lamb wave and the EMATs can be designed to excite very specific modes with unique relationships between the elastic constants and the wave velocities. The results of such measurements can yield the nine elastic moduli of commercial rolled plate as well as some measurements of the texture and can be used as a process monitoring tool[19, 20]. A detailed discussion of this technique can be found in a recently published handbook[21] on ultrasonic measurement of elastic properties.

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