Surface and Thin Volumetric Inspections with EMAT

Borja Lopez, Syed Ali, Victor Garcia

1 Innerspec Technologies, Inc, Lynchburg, VA, USA
2 Innerspec Technologies Europe, Madrid, Spain

blopez@innerspec.com

Abstract: Guided waves are widely used in non-destructive testing to cover long distances from one source point and to inspect hard-to-reach or inaccessible areas. Using reflection and attenuation methods, ultrasonic guided waves permit locating tight cracks, defects under coatings, and near surface defects that are undetectable with other NDT methods. While Conventional Ultrasonic Testing (UT) techniques require liquid or pressure coupling, Electro Magnetic Acoustic Transducer (EMAT) is a non-contact UT technique that generates ultrasonic waves on metallic materials using electromagnetic induction, thus circumventing the need to use liquid couplant. EMAT systems can be integrated in-line to inspect materials at extreme temperatures and fast production speeds.

Keywords: Electromagnetic Acoustic Transducer (EMAT); surface waves; guided waves; integrated systems.

1. Introduction

Detection of surface defects and near-surface defects can be of utmost importance on finished and semi-finished products. Surface defects on finished products can affect the look and performance of the finished part. On semi-finished products, a seemingly small surface or near-surface problem can increase in size or severity in subsequent processes with important economic consequences. The most common non-destructive inspection techniques for detection of surface and near-surface defects include vision (VT) –human or machine-, magnetic particle (MP), dye penetrant (PT) and eddy current testing (ET). All of them have advantages and disadvantages and are selectively used based on the requirements and environment of the application. MP and PT are typically used in manual or semi-manual operation on stationary objects or at low speeds, and only applicable to surface breaking defects. EC can detect surface and some sub-surface defects at high-speeds in automated environments, but it requires complete coverage of the area of interest, which can pose difficulties for integration. It also has limitations detecting long defects (along the longitudinal axis of the part), and flat type defects (lamina-tions). Machine vision systems have evolved greatly in the past few years and can be used to detect defects at high-speeds in production environments, but are limited to visible defects and cannot detect tight cracks. Ultrasonic guided waves have also seen many developments and increased use for many applications requiring high sensitivity to surface and near-surface defects.

2. Ultrasonic Guided Waves

Unlike more conventional bulk waves, guided waves propagate along a part while guided by boundaries, which directly affect the direction and mode of propagation. These boundaries can be a surface of a part or any elongated and relatively thin structure such as a rod, tube, plate or rail.

The most common types of guided waves are Rayleigh, Lamb, and Shear Horizontal (SH) waves.

Both Rayleigh and Lamb modes follow an elliptical pattern with vertical and horizontal particle motion. However, while a Rayleigh or surface wave has most of the energy concentrated on the surface and subsurface region within one wavelength, Lamb modes can penetrate several wavelengths and provide a complete volumetric inspection of the material. Both Rayleigh and Lamb waves can travel through long distances with strong particle motion. However, due to the motion in the vertical plane, they can also be attenuated by liquids or coatings surrounding...
the boundaries of the material subject of the inspection. Rayleigh and Lamb waves are the most common types of guided waves, and are frequently used for new products and in-service inspections.

Shear waves propagate perpendicularly to the wave direction, with different polarization depending on how they are generated. Piezoelectric transducers rely on refraction of longitudinal energy to generate Shear Vertical waves which are polarized at 90° from the entry plane. Using high-pressure coupling or electromagnetic induction (EMAT) it is possible to generate Shear Horizontal (SH) waves that travel parallel to the entry plane. As guided waves, SH modes are many times the only option for the inspection of pipelines, tank floors, and other structures where liquids, clamps or coatings would attenuate other wave modes with out-of-plane particle motion.

2.1. Guided Wave Equations

Although bulk and guided waves are fundamentally different, they are actually governed by the same set of differential wave equations [1]. Mathematically, the principal difference is that, for bulk waves, there are no boundary conditions that need to be satisfied by the proposed solution. In contrast, the solution to a guided wave problem must satisfy the governing equations as well as some physical boundary conditions.

For Rayleigh-Lamb modes, the frequency equations can be written as:

\[ \tan(qh) = \frac{4k^2pq}{\tan(ph)} = -\frac{4k^2pq}{(q^2 - k^2)^2} \]

for symmetric modes

\[ \tan(qh) = \frac{q^2 - k^2}{4k^2pq} \]

for anti-symmetric modes

Here \( p \) and \( q \) are given by

\[ p^2 = \left( \frac{\omega}{c_{L}} \right)^2 - k^2 \quad \text{and} \quad q^2 = \left( \frac{\omega}{c_{T}} \right)^2 - k^2 \]

The wavenumber \( k \) is numerically equal to \( \frac{\omega}{C_p} \)

where \( C_p \) is the phase velocity of the Lamb wave mode and \( \omega \) is the circular frequency. The phase velocity is related to the wavelength by the simple relation

\[ C_p = \left( \frac{\omega}{2\pi} \right) \lambda. \]

The Shear Wave equations can easily be solved for phased array \( C_p \) in terms of the frequency thickness product \( fd \) (where \( d = 2h \) and \( \omega = 2\pi f \)). The results is:

\[ C_p(fd) = \pm 2C_T \left( \frac{fd}{\sqrt{4(fd)^2 - n^2C_T^2}} \right) \]

When \( n = 0 \) (corresponding to the zero-order symmetric SH mode) we have \( C_p = C_T \), a dispersion-less wave propagating at the shear wave speed \( C_T \). All other SH modes (i.e., for all \( n \neq 0 \)) are dispersive.

3. Piezoelectric Vs. EMAT

The prevalent technique for generation of ultrasound is the piezoelectric transducer. While highly efficient and versatile, piezoelectric transducers need to be coupled to the part inspected either with high pressure, which limits the scanning ability, or with a liquid medium, which limits the deployment and can produce undesired interferences with the propagation of the wave.

EMAT or Electro Magnetic Acoustic Transducer is an Ultrasonic Testing (UT) technique that generates the sound in the part inspected instead of the transducer.

An EMAT induces ultrasonic waves into a test object with two interacting magnetic fields. A relatively high frequency (RF) field generated by electrical coils interacts with a low frequency or static field generated by magnets to generate a Lorentz force in a manner similar to an electric motor. This disturbance is transferred to
the lattice of the material, producing an elastic wave. In a reciprocal process, the interaction of elastic waves in the presence of a magnetic field induces currents in the receiving EMAT coil circuit. For ferromagnetic conductors, magnetostriction produces additional stresses that enhance the signals to much higher levels than could be obtained by the Lorentz force alone. Various types of waves can be generated using different combinations of RF Coils and Magnets.

Because the sound is generated in the part inspected instead of the transducer, EMAT has the following advantages over more conventional piezoelectric transducers:

- **Dry inspection.** EMAT does not require couplant for transmitting sound, which makes it very well suited for inspection of very hot and very cold parts, and integration in automated environments.
- **Impervious to surface conditions.** EMAT can inspect through coatings and are not affected by pollutants, oxidation, or roughness.
- **Easier sensor deployment.** Not having wedges or couplant, Snell’s law of refraction does not apply, and the angle of the sensor does not affect the direction of propagation. This makes EMAT transducers easier to control and deploy.
- **Ability to generate SH modes.** EMAT is the only practical means for generating shear waves with horizontal polarization (SH waves) without high mechanical pressure or low-density couplants that impede scanning of the part.
- **Mode selectivity.** The antenna-type construction of the EMAT coil combined with a multi-cycle excitation provides great specificity in the frequency domain, thus the ability to precisely select the wave mode of interest, which is of great importance for guided wave generation and interpretation.

4. **Practical Applications**

There are many well-known applications for in-service inspections using guided waves such as LRUT – Long Range UT (stationary ring inspection with tubular waves), and MRUT - Medium Range UT (circumferential and axial scanning with plate waves). There are also very successful applications with hundreds of installations using EMAT-generated guided waves for inspection of thin welds [2].

In this paper we will concentrate on more recent applications of EMAT for surface and volumetric inspections in factory environments.

4.1. **Surface Inspections**

4.1.1. **Inspection of Round Billets**

This application involved the inspection of round billets at the exit of an annealing oven with a surface temperature of 350°C. The requirements included the detection of longitudinal, surface breaking cracks propagated from the inside of the billet, and folds on the surface of the billet caused by the rolling process. A rotary eddy current system was dismissed due to the temperature and large dimensions of the billets, which would have made the system too costly and cumbersome.

The final solution required only two surface-wave EMAT transducers located at different locations of the billet and sending sound around its circumference. The system used a wavelength of 4mm and was capable of detecting cracks and folds as small as 0.4mm in depth.
4.1.2. Inspection of Copper and Brass Plates

The application required the inspection of flat copper and brass plates before their introduction in a rolling mill. The two-meter-wide raw plates are fed into a scalper that removes the top-most layer of the plate to eliminate surface imperfections prior to rolling. The customer had installed a machine vision system after the scalper to determine if all the imperfections had been removed, but the system proved inadequate to detect tight cracks, and produced a lot of false positives due to the rough texture left by the scalping process.

The project included on-site tests using a portable system to fine-tune the equipment and determine the capabilities of the technique. After successful proof-of-principle tests, the customer installed an automated integrated system.

4.2. Volumetric Inspections

4.2.1. Inspection of Multi-Layered Clad Products

Multi-layered composites are widely used to enhance the structural capabilities of different materials. In composites created by cladding or adhesive bonding, delamination is an ever-present risk that can compromise the quality of the final product. Timely detection of potential
Delamination is very important to save production cost and prevent consequent failure [3].

The product in this case included single and three layer combinations of brass/copper/brass, nickel/copper/nickel and other materials used for the manufacture of coin stock. The customer had previously tried EC and normal beam UT to detect delaminations without success.

The selected EMAT technique included two transmitters on one side of the strip sending Lamb waves to receivers on the other side of strip. The receivers measured signal amplitude and Time-Of-Flight variations caused by delaminations and other imperfections in the strip.

After extensive modeling and empirical tests on the three-layer composite, it was discovered that the responses followed a cyclic behavior related to the dimensions of the lamination. At the delaminated region, the incident guided wave mode decomposed into wave modes in two sub-systems, one at the delaminated layer, and the other on the other two. At the end tip of the delamination, the two waves converted back to the wave modes in a three layered structure. Since the EMAT receiver has an effective mode selection, the amplitude of the receiving signal was strongly affected by the amount of energy converted back to the incident mode.

The equipment included a double frequency technique to take into account and compensate for this cyclic behavior.

The final system was able to detect laminations as small as 1cm² at over 1m/s. It was subsequently replicated with different integration patterns at other coin stock manufacturers with similar success.

5. Conclusions

There are many techniques for surface and near-surface inspection of parts with their own advantages and limitations.

Ultrasonic guided waves are growing in popularity due to their high sensitivity to surface and internal defects, and their ability to cover large spans at a distance and with a limited number of sensors. While guided waves are well documented for in-service inspections, their use in factory environments is less known by the NDT community.

In this paper we emphasize the unique advantages of Electromagnetic Acoustic Transducer (EMAT) for generation of guided waves, and integration in production environments.

To conclude, we introduce a new generation of NDT systems for surface inspection of long products and volumetric inspection of single and multi-layered strip in factory environments. These systems follow the success of guided waves for thin-weld inspections, and underscore the increased role of guided waves for inspections in factory environments.

References