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# APPLICATION EXAMPLES OF EMAT GENERATED HORIZONTALLY POLARIZED SHEAR WAVES FOR ULTRASONIC INSPECTION

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## ABSTRACT

Some inspection applications can be greatly improved by the use of shear horizontal waves. In this work, various examples of the uses of ultrasonic horizontally polarized shear (SH) are presented. The ultrasonic waves used in all of the applications examples were generated using Electromagnetic Acoustic Transducers (EMATs) couplantless technology. The inspection were performed using either the traditional bulk inspection or with the non-conventional guided wave inspection methodology. The purpose of the review paper is to demonstrate both the advantages and disadvantage of SH waves inspection performed with the EMAT probes. Individual application examples include a brief description of the problem; the inspection methodology using SH waves and finally some results and comments of SH waves inspection. The examples investigated include methodology for defect detection and integrity assessment.

## SH WAVES

SH waves have a propagation displacement, characterized by a null normal displacement on the surface of the material and a particle displacement perpendicular to the propagation direction and always parallel to the surface Auld (1). This feature provides a number of significant advantages over conventional ultrasonic waves. These waves are insensitive to loading; therefore there are no leakage losses in acoustic media such as tar, coatings and water. They do not suffer mode conversion at defect interfaces, a fact, which enhances received signal quality since the reflected signals are not encumbered with the noise of parasitic conversion signals and there is no conversion loss of energy. The displacement of SH waves is illustrated in Fig. 1, and compared to the SV (shear vertical) wave which as an oscillation component having an angle to the surface.

## EXCITATION OF SH WAVES

SH waves were generated in the structure using an EMAT (2, 3). Due to the difficulty of excitation and generation of SH waves, an EMAT is an excellent device, providing the capability to match the excitation force with a specific particle motion. When SH-waves are introduced using these transducers, a number of experimental variables that could not be controlled with specially cut piezoelectric transducers can be selected through frequency adjustment. Frequency control permits wave modes to be generated individually in a given structure. Another advantage of using EMATs is that they do not require a liquid couplant, making it simple to scan the inspection structure. SH wave inspection scans cannot be performed with piezoelectric transducers since they require a viscous couplant to generate horizontally polarized shear oscillations in the material. EMATs can also generate SH-waves over layers of rust or dirt of thickness less than 1-2 mm.

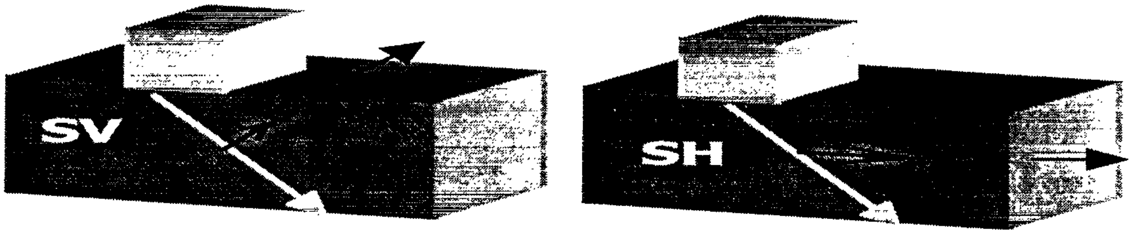


**Figure 1 Shear oscillation in material for Shear Vertical (SV) and Shear Horizontal (SH) waves**

GUIDED WAVE INSPECTION

SH can propagate as plate waves and be used for guided wave inspection. These waves can propagate in plate-like structures of a few wavelengths thick or even of the order of one wavelength. They are, as Lamb waves, two dimensional stress waves in infinite plate structures whose surfaces are free of stresses. Their propagation characteristics are tailored to the geometry of the structure inspected (the elastic wave-guide). Their elastic motion covers the whole thickness of the structure (wave-guide) due to the guiding effect of the inner and outer surfaces of the pipe. SH–plate waves have small divergence losses and are attenuated less rapidly than bulk waves, resulting in longer propagation ranges than those for bulk waves with the same frequency and higher sensitivity for defect detection. Therefore, SH-plate waves can propagate for distances of several meters in pipes having a thickness of several millimeters. Furthermore, SH-plate waves can follow curvature thus enabling inspection along bends and other irregular geometry.

Unlike longitudinal and shear bulk waves, SH-plate waves offer improved inspection potential due to the availability of a host of different propagating modes, each with its own unique characteristics. Modes can therefore be selected to enhance detection of different types of defects such as cracks, holes, and corrosion. SH-plate waves were used (6-8) in various applications.

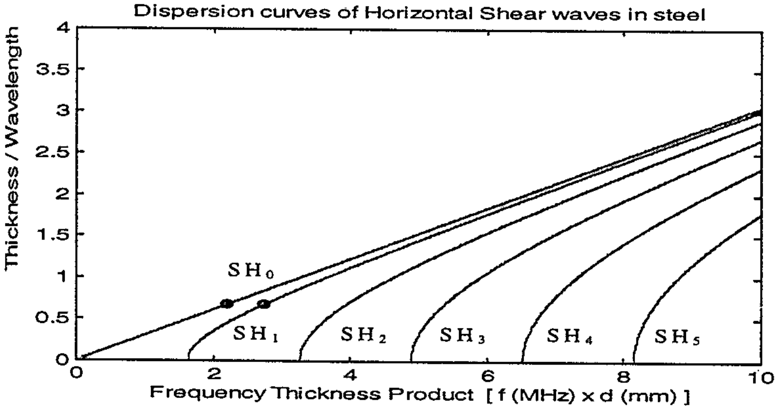


**Figure 2 Dispersion curves for SH modes in plates**

Prior to investigating detection and interaction of SH wave modes with defects in materials it was necessary to represent their theoretical dispersion curves. This was required to verify the group velocity of the pre-selected modes and to select the frequency on the dispersion curves at which these modes are excited. Dispersion curves depend upon material properties and specimen geometry; in this case the curves are for a steel plate. The curves in Fig. 2 describe the relation between the plate thickness to wavelength ratio versus the frequency-thickness product for the first 6 SH modes.

## VERTICAL SPLIT HEAD IN RAILS

The vertical split head defect is a progressive longitudinal fracture in the head of the rail, where separation spreads vertically through the head at or near the middle of the head, Fig. 3.

It is difficult for traditional ultrasonic methods to detect such a defect because of the 0° degree inclination and the orientation in the rail head transversal direction. To improve railroad track inspection reliability a new inspection technique was develops using the oscillation propriety of SH waves. The method consists of generating a bulk Shear Horizontal wave generated with EMAT at 0°, with a shear oscillation polarization direction selected for maximum defect interaction. This polarized oscillation direction is perpendicular to the defect plane as shown in Fig. 4.

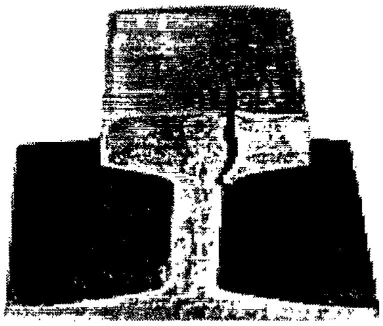


**Figure 3 Vertical Split Head in rail**

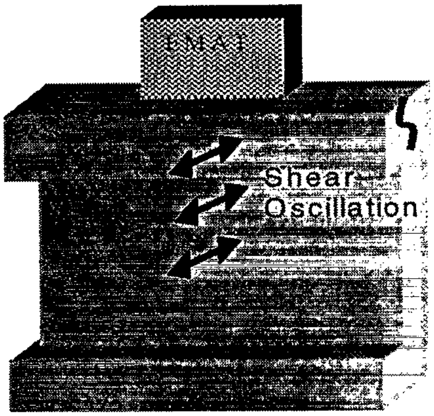
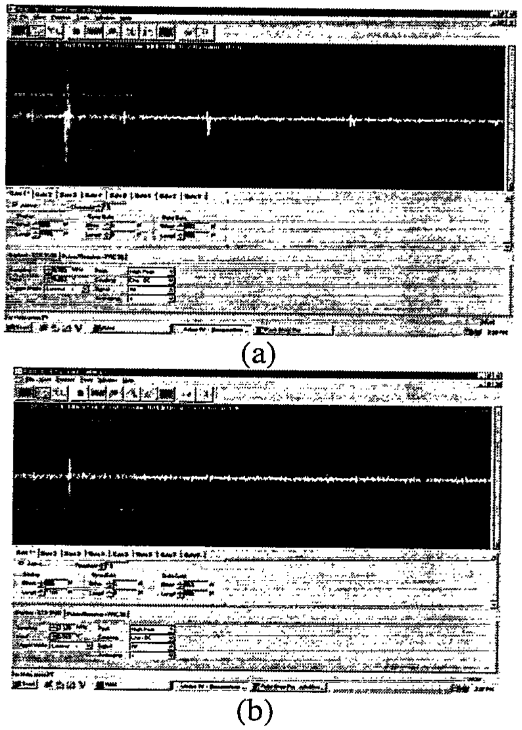


**Figure 4 Shear horizontal oscillation in rail**

The linearly polarized shear oscillation causes a particle displacement perpendicular to the faces of the vertical split head; therefor a SH wave launched in the railhead will be strongly attenuated if a Vertical Split Head. Fig. 5a shows the multiple back wall reflection of a bulk SH waves generated in a defect free rail, and, Fig. 5b shows the same wave launched in a rail having a vertical split head. In some cases the wave-defect interaction can cause the appearance of an extra reflection from the tip of the vertical split head. The disadvantage of such a method is the lack of a clear reflective indication of the presence of a defect, and loss of back wall could be attributed to other factor such as surface conditions enabling the generation of waves in the material.


(a)

(b)

**Figure 5 Back wall reflections from rail without VSH (a) and with VSH (b)**

WELD INSPECTION

Weld inspection is one of the most common applications of UT inspection. Traditional shear vertical waves have demonstrated good and reliable defect detection ability, however the advantages of using SH wave lies in some specific cases of weld inspection. These would be in cases were the use of couplant is impossible because of rust or high temperature conditions or and in cases were mode conversion prevent reliable inspection results because of an excessive amount of spurious echoes.

In this short paper a simple cases is presented to demonstrate the capability of EMAT SH wave inspection. Inspection was performed on 25.4 mm thick steel plate having a weld in which two lack of fusion defects were introduced. This weld was inspected with a 45$^0$ shear vertical generated with a piezoelectric and a wedge and a 35$^0$ shear horizontal waves generated with an EMAT. The purpose of this inspection was to demonstrate the feasibility of weld inspection using SH waves. The EMAT probe not being optimized for this particular application the signal to noise ratio (SNR) is very low, but the lack of fusion could have been detected at high temperature without any couplant.

Fig. 7 shows the results of these two inspections. The B-Scans images reveal the presence of the two lack of fusion defect.

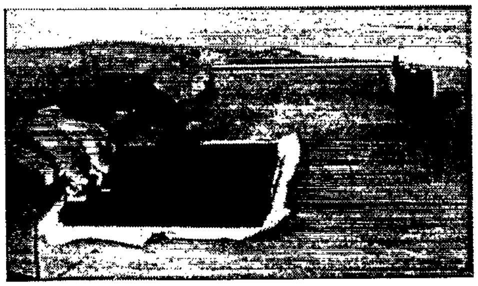
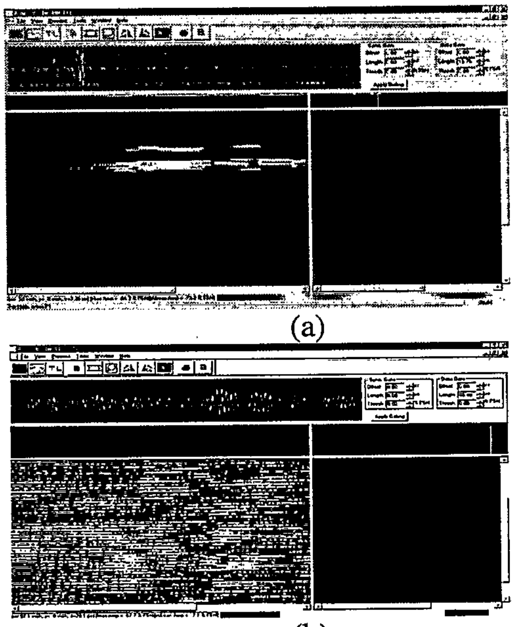


**Figure 6 Ultrasonic inspection of weld using a manual scanner**

PIPELINE INSPECTION

Defects found in these steel structures range from large discontinuities to small and subtle deterioration process defects such as stress corrosion cracking (SCC). Standard ultrasonic techniques applied for the non-destructive testing (NDT) of pipes include the straight beam method using longitudinal waves and the angle beam method using vertical shear (SV) waves. Although these methods have proven effective they do not have the advantages of SH waves, which could provide a sensitive, fast, and cost effective NDT method to detect, locate and validate discontinuities due to a variety of materials deterioration mechanisms. The application example for this inspection uses of SH guided waves to inspect circumferentially the pipe wall using a single transversal line (4,5).



(a)

(b)

**Figure 7 Detection of two lack of fusion in weld using piezoelectric (a) and using EMAT (b)**

Defects were introduced in the cylindrical sample on the inside or outside surface of the pipe wall. After optimization of the power distribution of the modes two inspection modes were selected the SH$_0$ and SH$_1$ mode. These two modes were generated with a single bi-modal EMAT.

The first set of results, shown in Fig 8, are A-Scans of the signal in the pulse echo mode from three defects located in the same circumferential path for the SH$_0$ and the SH$_1$ modes. These defects had different depth ratios: 10% (D$_1$), 30% ( D$_2$ ), and 50% ( D$_3$ ). For the first graph, 6a, the EMAT was placed at 224 mm from the 30% defect (D$_2$). The defect caused a good reflection, however the energy loss was sufficient to reduce considerably the reflection from the second defect (D$_3$ - 50% depth ratio). The SH$_0$ was barely sensitive to the 10% (D$_1$) defect. For the SH$_1$ mode the probe was placed at 140 mm from the 10% defect and the two consecutive defects (30% at 540 mm and 50% at 760 mm) were also detected, although the SNR was reduced appreciably by the presence of D$_2$. This is shown in Fig. 8b. This representation demonstrates that SH guided waves are sensitive to the axial defect and that it is possible to detect a series of defects located in line with each other if the depth of the defect is smaller than the effective sound beam.

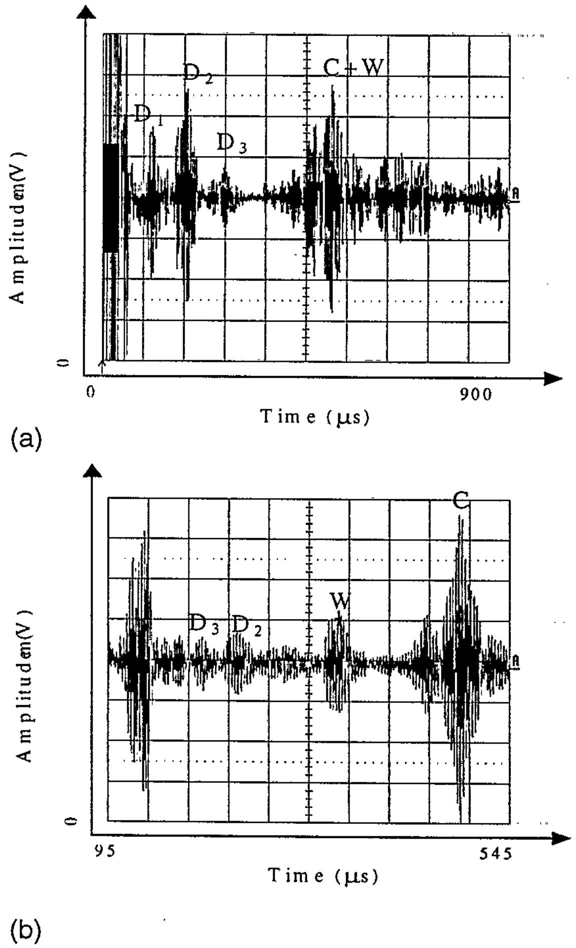


**Figure 8 A-Scan display of propagation of (a) SH$_0$ mode and (b) SH$_1$ mode around pipe with three defects**

The automated scans, as shown in Fig 9 were performed to assess the ability of the SH waves to discriminate between closely aligned defects. Using this setup EMAT probe can easily slide over rust layers, welds or imperfections and the coil surface can be adapted to surface curvature.

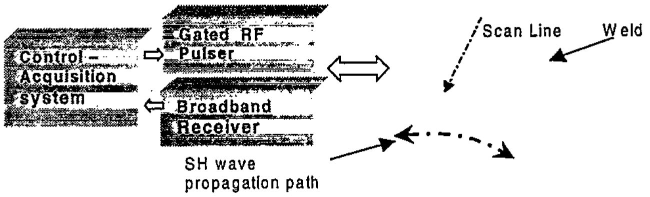


Figure 9 Inspection setup for pipeline scans

The scans were performed with the EMAT located at 300 – 400 mm from the defect region. The B-Scans are shown in a 3-D visualization view for which the amplitude is both color coded in a gray scale format and plotted in the z-axis. The scan is in the x direction, and the time of flight (propagation direction) is in the y direction. The B scan, Figure 10a, shows the image from a single defect scanned with the $SH_0$ mode. The second image, 10b, shows the image resulting from scanning three defects separated by 10 mm in the axial direction. The last one, 10c, shows the image resulting from three defects separated by 12.7 mm in the circumferential direction. These B-Scan images demonstrate that defects can be isolated in the axial direction but not as easily in the circumferential direction.

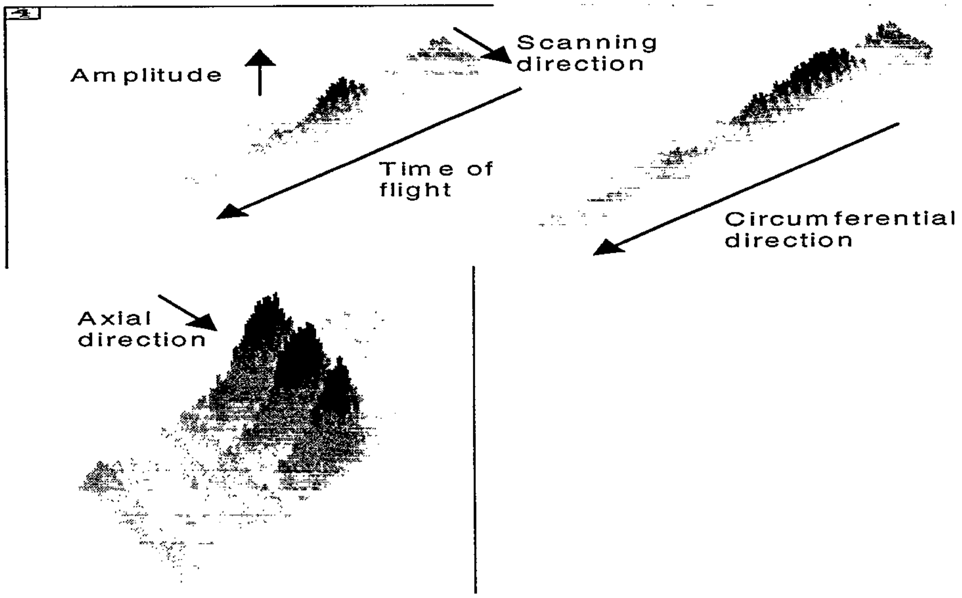


Figure 10 B-Scan image of (a) single defect, (b) four defects separated circumferentialy and (c) three defects separated axially

## DISBOND DETECTION WITH GUIDED SHEAR WAVES

Another advantage provided by SH waves is their sensitivity to adhesion defects (6) such as disbond between coating and pipe wall, a site favorable to corrosion problems.

The basic idea in this work relies on inspection with selected horizontal shear wave modes with sufficiently high amounts of ultrasonic energy, which will ensure maximum interaction with the bond-line region to provide information of the adhesive adherent interface. Any material changes such as weak bonding or lack of adhesion between the two inspected layers will affect the propagating (or reflected) mode amplitude, velocity, frequency spectrum and time-of-flight. This measurement information can be then correlated to the bond quality.

For example, inspection of lap joints with guided shear waves in a pitch-catch setup is shown in Figure 11. A good bond will permit the excited wave mode to travel from sender to receiver probe producing relatively high RF signal amplitude. Low RF signals will be received for a disbond since the energy of the transmitted mode will not leak into the second joint. In a pulse-echo setup, the wave will travel from the sender/receiver probe producing relatively high amplitude RF signal when a disbond exists between the two bonded layers. This high amplitude corresponds to reflection from the disbonded region where the transmitted energy does not leak into the other plate but hits the free edge of the plate and reflects back to the transducer in the receive mode. In the case of a good bond, the amplitude is lower because we have leakage of the transmitted energy into the bonded plate.

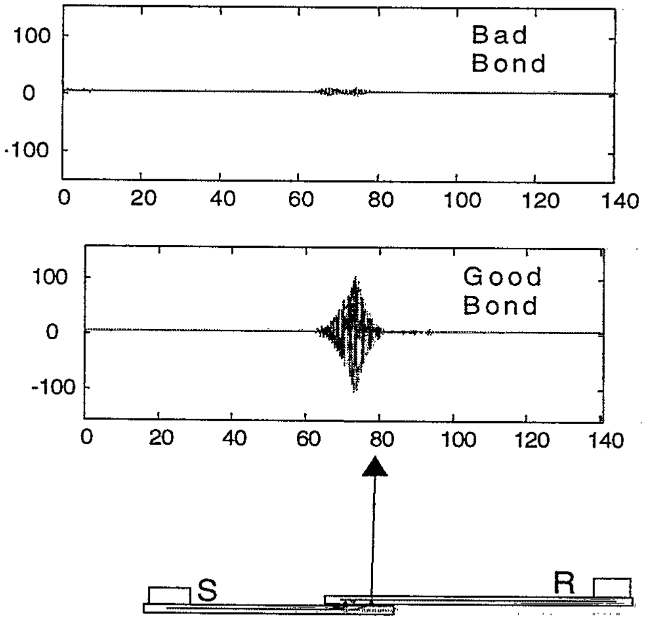
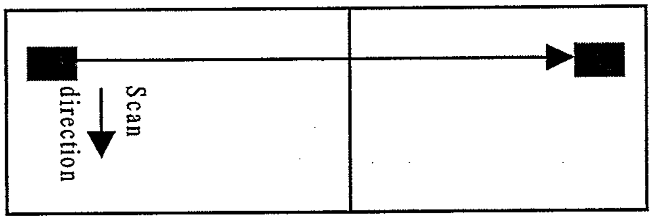


Figure 11 Lap joint transmission results from a) good bond b) bad bond

Disbond assessment in a simulated lap splice joint structure was obtained using pitch-catch setups. EMAT probes with a 3 mm wavelength were used to excite $SH_0$ and $SH_1$ at 1.044 and

1.305 MHz. In this test, a single line was scanned by automatically moving the transducer pair along the specimen to compare signals obtained through the well-bonded and disbonded areas. Figures 12a and 12b show the results of pitch-catch inspection. Signals from these two scans were collected and presented in a two-dimensional B-scan format. The well-bonded areas are characterized by high-amplitude signals (most of the energy is transferred to the second part of the joint). Poorly bonded areas resulted in low amplitude of the reflected signals (signals indicated by blue color) since little transfer of energy between the two parts of the joint takes place. To verify the guided wave results, the simulated specimen was also inspected using an automated eddy-current scanner. Disbonds were detected in the middle of the specimen by both techniques as shown in Figure 12a, 12b and 12c. The light gray colors in the eddy current image show good bonded regions while the dark gray represents areas having disbonds.



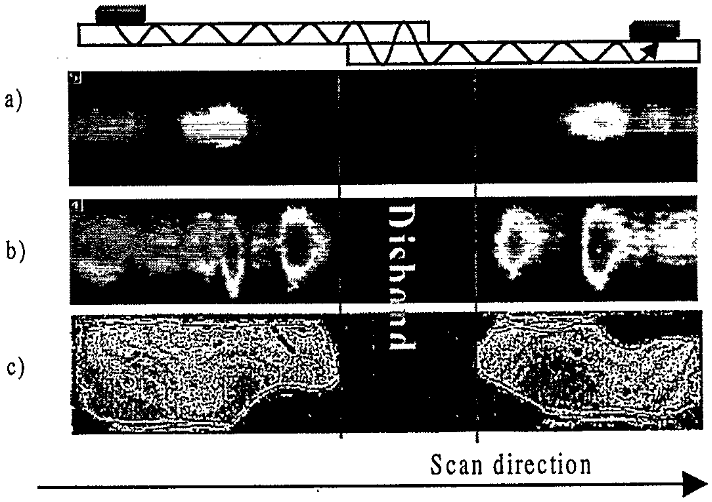


**Figure 12 Inspection results of a disbonded sample using (a) SH$_0$ mode, (b) SH$_1$ mode and (c) using Eddy Current**

## CONCLUSION

The results found in this preliminarily work demonstrates the potential of using SH waves for rapid inspection of various structures. SH waves can be used in specific applications were SV waves are not suitable for reliable inspection. SH are best generated with EMAT probe; for guided wave generation the signal to noise ratio is excellent, however for bulk inspection efficient generation of SH waves require a careful design of the EMAT probe. Guided SH modes can be complimentary to one another for detection of defect and integrity assessment. EMAT technology to generate SH waves can be used for automated scans of either aluminum or steel large structures.

## REFERENCES

1. B.A. Auld, Acoustic Filed and Waves in Solids" Vol. II, John Whiley & Sons, New York, 1973

2. R.B. Thompson, "Physical Principles of Measurements with EMAT Transducers", Physical Acoustics, Vol. XIX, Academic Presses, 1990, pp. 157-200

3. B.W. Maxfield and C. M. Fortunko, " The Design and Use of Electromagnetic Acoustic Wave Transducers", Material Evaluation, Vol. 41, November 1983, pp. 1399-140

4. H.J. Salzburger, "Long Range UT by Structural Ultrasonic Waves and Electromagnetic Acoustic Transducers (EMAT)", 16th Major International Ultrasonic conference and Exhibition presented by Hawksmere, 5-7 July, 1995, Edinburgh.

5. J.L. Rose, D. Jiao and J. Spanner, "Ultrasonic Guided Waves for Piping Inspection", Review of progress in Quantitative NDE volume 15, 1996, pp. 1285-1290

6. C.H. Yew, "Using Ultrasonic SH Waves to Estimate the quality of Adhesive Bonds: A Preliminary Study", J. Acoust. Soc. Am., 76 (2), August 1984, pp. 525-531