New technique for ultrasonic inspection of multi-pass welds with EMAT guided waves

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Abstract. Multi-pass welding is typically employed to join thick-walled plates or pipes. This welding technique is very common in many industries such as ship building, pressure vessels, nuclear or oil & gas. Normally, these welds can only be inspected at room temperature using conventional non-destructive testing techniques, which are slow and time-consuming processes. Once a defect is located in the weld, the weld needs to be grinded down or cut out and re-worked which is not only expensive but also adds additional wastage of time. This paper presents a novel technique using Rayleigh and Shear Vertical waves generated with electromagnetic acoustic transducers (EMAT) which aims to control the quality of partially completed girth welds and may be considered in the future for the inspection of each weld pass during welding process in a relatively hot state, providing real-time inspection and quality control.

1. Introduction

Recently the requirements for pipeline girth welds inspection have become more and more stringent, especially for clad pipes using Corrosion Resistant Alloy (CRA). These thick multi-pass welds need to be completed first, followed by cooling-down time and then inspected using conventional non-destructive techniques. If a defect is found in the weld zone the weld needs to be grinded down and re-worked. This process is extremely expensive for thick welds and also time consuming.

The method developed by Innerspec Technologies in collaboration with Saipem S.A. employs EMATs generating Rayleigh and Shear Waves enabling real-time scanning of each weld-pass to detect possible defects and fine tune weld parameters [1]. The EMAT sensor can be attached to an automated welder which follows the hot weld at some distance and provide information of the integrity of the weld before more weld passes are laid down, thus reducing consumption of material and time. The EMAT developed for this application can be used on hot surfaces up to 300 ºC. Earlier detection of flaws in these thick multi-pass welds is the key to reduce wastage, improve weld parameters and be efficient in time. Additionally, it may also be able to replace the possible intermediate radiography of partial welds in suspected cases.

Previous work in this area includes development of a vision-based system which measures the weld bead and possible visible defects using complex vision-based techniques [2]. Researchers have also attempted using conventional ultrasonic longitudinal waves from the edge of the base material [3] with a limited success. None of these methods are widely used in industry due to their complex data analysis mechanisms, inability of operating at relatively high temperatures and inability to detect defects with high confidence levels. The real-time inspection of these thick multi-pass girth welds for pipes at high temperatures is still a challenge.

EMAT as an alternative and new ultrasonic testing method can be used to generate Rayleigh or Shear Vertical (SV) waves without using liquid couplant. As a result, EMAT in principle is very suitable for inspection of hot surfaces with all the benefits inherent from an ultrasonic testing, [4] , [5] and [6]. As a brief summary, the following are the advantages of using EMAT for the inspection of multi-pass welds:

- The inspection is sensitive to structural critical discontinuities.
- The inspection is dry, no chemicals and hazardous materials involved in the inspection.
- Suitable for high temperature applications and test pieces with certain surface roughness.
- EMAT generated waves can propagate and inspect a large area with sensors at one location, large sensor array is not necessary.
- Can be integrated into automated inspection systems at high speed.

2. EMAT generated Rayleigh and Shear Vertical waves

Rayleigh wave or SV wave generation using EMAT can be achieved by using a meander coil in a magnetic field as shown in **Figure 1.** The meander coil excited with an alternating RF current when placed near a conducting material generates time varying eddy currents in the material which in turn generates its own alternating magnetic field. This alternating magnetic field when interacts with the bias magnetic field generates Lorentz forces creating ultrasonic vibrations. Depending upon the periodicity of the meander coil and the frequency of excitation both Rayleigh and SV waves can be generated.

The Rayleigh waves tend to propagate near the surface of the material penetrating approximately a wavelength into the material, whereas SV waves are generated at an oblique angle propagating through the material thickness. Theoretically this process may also generate a very weak longitudinal wave in the material which attenuates quickly and was of no significance during field tests.

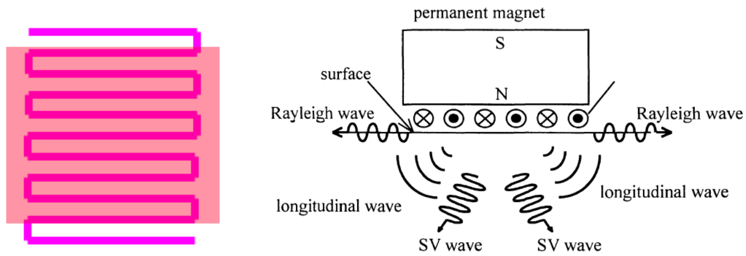


Figure 1 Ultrasonic waves generated by a permanent magnet and meander coil [7]

A proper excitation frequency on the EMAT meander coil together with a normal magnetic bias, can favor the generation of either the Rayleigh or the SV waves according to the following expressions:

$$Frequency_{Rayleigh} = \frac{0.92 * V_{shear}}{\lambda} \quad (1)$$

$$Frequency_{SV} = \frac{V_{shear}}{\lambda \sin \alpha} \quad (2)$$

where

λ: wavelength
V_{Shear}: Shear sound velocity on steel
α: angle of the sound beam

In case of EMAT generated SV waves, the earlier work suggests that maximum efficiency or strongest SV wave can be generated when the angle of excitation is approximately 35º [8].

The simulated beam profiles beam profiles for a 2.5mm meander coil excited at the Rayleigh and SV for 35º frequencies can be seen on **Figure 2**

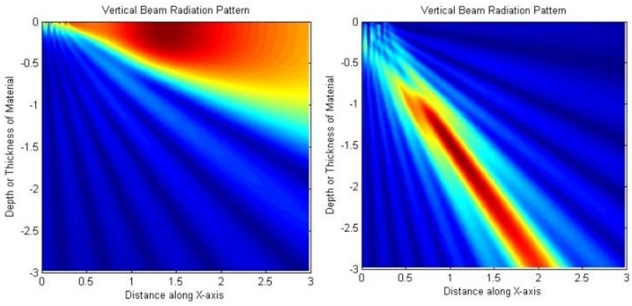


Figure 2: Simulated beam profiles for 2.5mm meander coil excited at Rayleigh and SV 35º frequencies

3. Inspection strategy

EMAT generated Rayleigh waves have already been used in the inspection of multi-pass welds in pitch-catch configuration. The transmitter is placed on one end of the weld bevel and receiver is placed on the opposite end. The energy passes through the weld and is collected by the receiver on the other end. In the presence of a defect this energy attenuates thus indicating a possible failure [9].

The surface wave while propagating through the complex geometry loses energy due to possible reflections, scatterings and mode conversions when interacting with bevelled edges and narrow groove deep weld. The energy received at the opposite end by the EMAT receiver in the absence of defects establishes a baseline. The same energy when interacts with a defect in the weld produces additional reflections and scatterings **(Figure 3)**. This phenomenon reduces significantly the amplitude of the received energy indicating the presence of a possible defect.

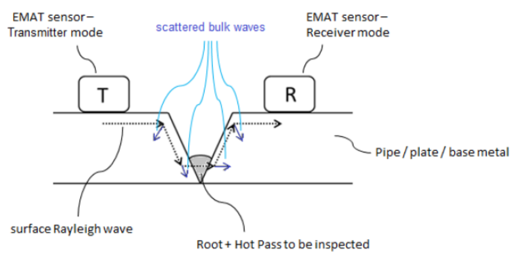


Figure 3: Surface Rayleigh wave propagation through the weld root pass disturbed by ultrasonic reflection and scattering effects

The depth of penetration for ultrasonic Rayleigh wave is dependent upon the wavelength of the meander coil and wave propagation length through the throat of the weld bevel. The root pass being the lowest in the bevel requires longer propagation distance of the energy travelling through the bevelled path and thus may result in less sensitivity, whereas each subsequent pass filling the bevel reduces the propagation path of surface wave providing higher sensitivity. To improve sensitivity at root pass and the first passes near the root level, the surface wave technique is complemented with SV waves at an oblique angle of 35 degrees. This SV wave technique can be used in pitch-catch and also in pulse-echo configurations. (**Figure 4**)

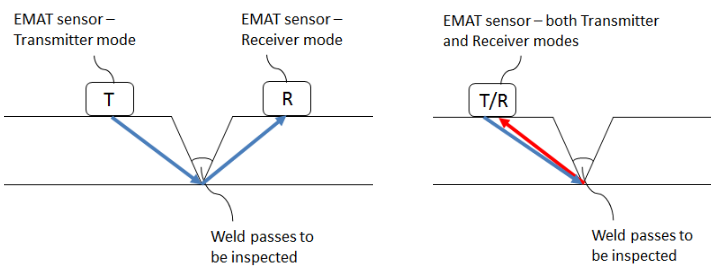


Figure 4: Shear Vertical in pitch-catch and pulse-echo configuration

Figure 5 shows the sensor deployed for the inspection of pipe with OD 14” x 19.1mm WT – J-bevel girth weld. Using pitch-catch technique, the energy acquired by the EMAT receiver is gated. **Figure 6 (a) (b)** show two typical AScan signals from Rayleigh wave configuration in pitch-catch. The first image is at a defect-free location in the weld, whereas the second picture shows an area with lack of fusion. The maximum amplitude detected on the gates is monitored using a strip line as shown in **Figure 6 (c)** which plots the gated amplitude versus the scan distance. On the other hand, for the pulse-echo configuration the amplitude is expected to remain low in the absence of defect, whereas in a defective area the energy will be partially reflected back as shown in **Figure 6 (d) (e)**.

It is important to note that in some cases strong geometrical reflections can be obtained along the complete weld seam, due to deep irregular root or part misalignments, which can obscure the reflection from possible defects as the baseline signal response will be higher. In such cases, the SV wave in PE would also fail to provide any meaningful detection of weld defects.

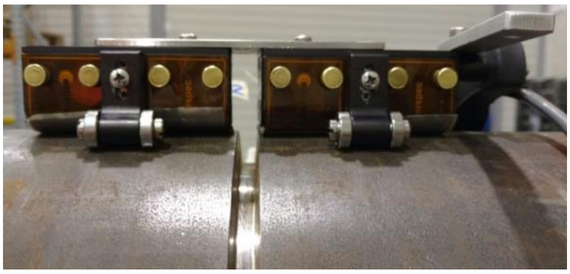


Figure 5: EMAT Sensor disposition on OD 14” x 19.1mm WT – J-bevel girth weld

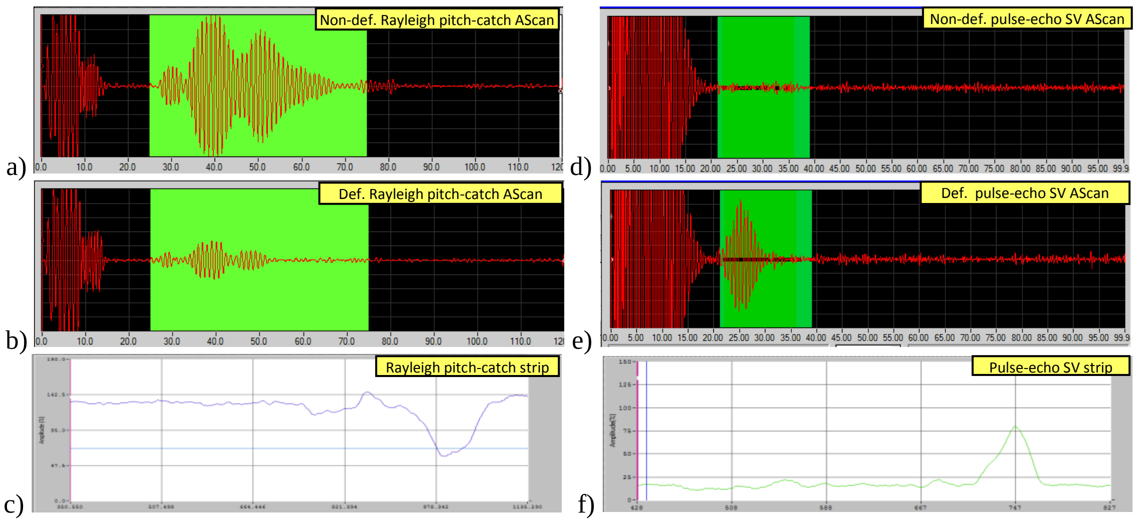


Figure 6: Collected data from OD 14” x 19.1mm WT – partial J-bevel girth weld **a)** Rayleigh wave pitch-Catch AScan from an area free of defects. **b)** Rayleigh wave pitch-Catch AScan from an area with a lack of fusion. **c)** Strip line plotting maximum amplitude versus circumferential scan position for Rayleigh waves in pitch-Catch configuration. **d)** SV waves in pulse-Echo AScan from an area free of defects. **e**) SV wave in pulse-Echo AScan facing a lack of fusion area. **f)** Strip line plotting the maximum amplitude for SV waves in pulse-Echo configuration.

4. Experimental verification

To test the feasibility of the described procedure, two defective partial welds with natural flaws were produced by configuring the welder with intentionally erroneous parameters by Saipem. The samples include Carbon Steel partial welds – OD 14” x 19.1mm WT – J-bevel and a CRA clad partial manual welds – OD 14” x 24 + 3mm WT – V30° bevel. The welds contained defects such as continuous and intermittent lack of penetration (LOP), cluster porosity, and continuous and intermittent side lack of fusion (LOF). **Figure 7** shows the testing specimens.

Figure 7: Testing Welds

The results obtained on the defective partial welds are presented on **Figure 8**

In order to reduce the signal fluctuations due to geometry and surface conditions, the received amplitude has been normalized and an adaptive threshold has been defined for these tests. The areas free of defects with the signal far from the threshold were labelled as A (green) while the areas where the threshold was violated or crossed due to a possible defect were labelled as B (red). The areas where the signal was close to the threshold without crossing it or where the threshold was crossed and no defect was expected were also considered for further evaluation and received a C (yellow) and D (orange) labels correspondingly.

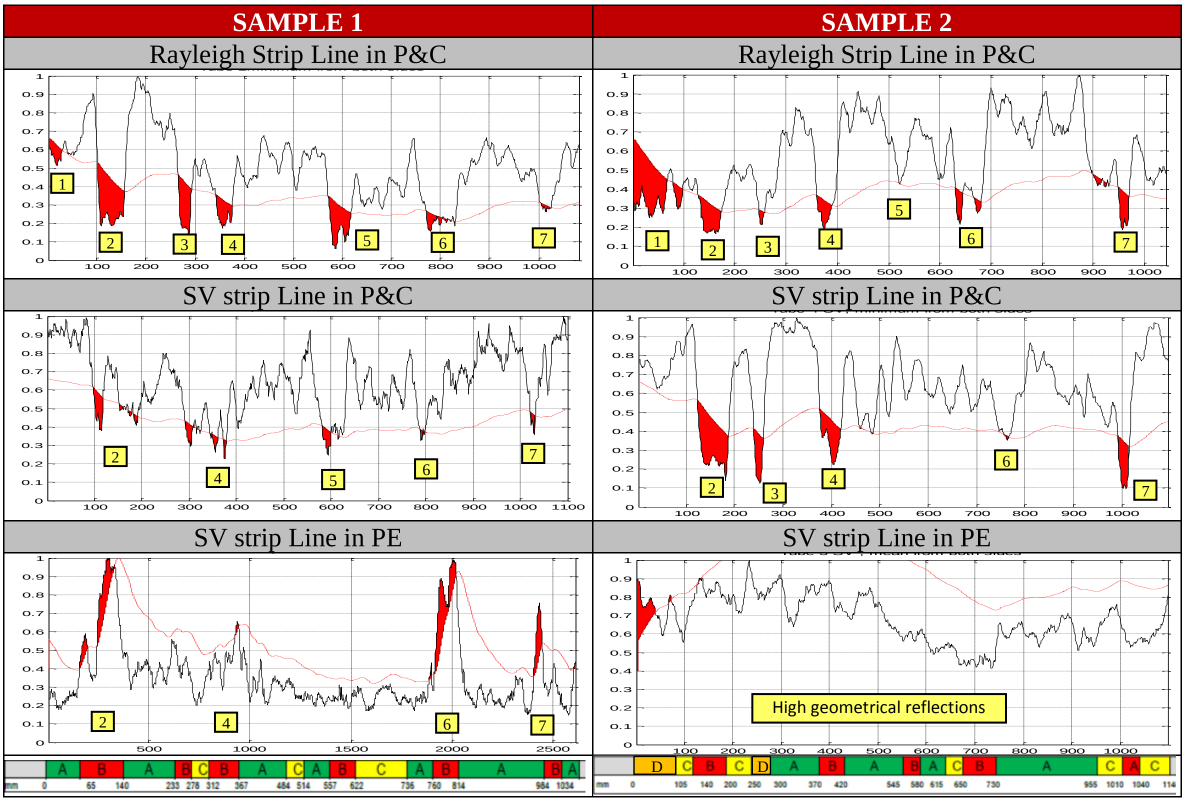


Figure 8: Strip lines for the Rayleigh pitch-Catch, SV pitch-Catch and SV pulse-Echo inspections of CS OD 14" x 19.1mm WT-J-bevel and CRA OD 14" x 24 + 3mm WT–V30°

For evaluating the EMAT sensitivity and the size of the estimated defects, the samples have been radiographed and also destructively tested (DT-macrographs). Other areas where the EMAT system indicated defects contrary to the radiographies were also examined and found defective by DT. An analysis of all the tests conducted with EMAT and the other techniques are presented in **Figure 9** and **Figure 10.** Overall the comparison of all techniques establishes the effectiveness of EMAT multi-pass welds inspection as good as the other techniques. Some of the pertinent results from these tests can be summarized as follows:

- Small Porosities (Ø < 1mm) seen by RT are missed by EMAT, due to poor resolution (being placed at the same circumferential location as other planar flaws) or because although a drop of amplitude is observed is not enough to break the threshold. This fact can be palliated using a more restrictive threshold.

- Some areas were assessed as defective areas by EMAT only. These areas were selected for macro-sectioning, in order to confirm the existence of weld imperfections that intermediate RT failed to detect. The micrographic images are deployed on **Figure 11**
    - One sidewall Lack of Fusion 0.8mm x 20mm in hot pass (**Figure 11 -M6**).
    - EMAT detected a pipe lamination imperfection not located on the weld (**Figure 11-M5**)
    - EMAT detected a bevel mark resulting from an arc-strike (**Figure 11-M4 and M5**)
- No missed flaw has been monitored during macro-slicing activity.
- Globally, EMAT system shows a detectability at least as good as IRT.

SAMPLE 1					
Flaw description	**EMAT indication (Figure 8)**	**EMAT length estim. [mm]**	**RT length estim. [mm]**	**Macro section**	**Macro length estim. [mm]**
Porosity	1	20	<1	-	-
Interminet LoP	2	75	52	-	-
LoF+Crater cavity	3	45	9	M1	20
LoP	4	55	48	M2	30
Porosity Cluster	5	65	50	M3	40
LoF	6	54	61	-	-
LoF	7	50	38	-	-

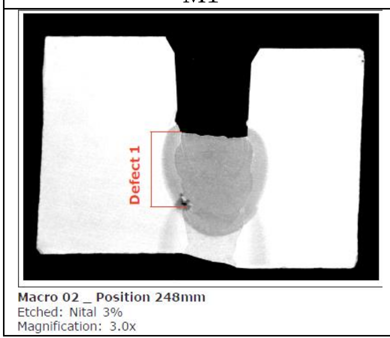
Figure 9: Sample 1: (DNV 450 SMLS grade OD 14” x 19.1mm WT– J-bevel) EMAT, RT and macro sectioning results comparison

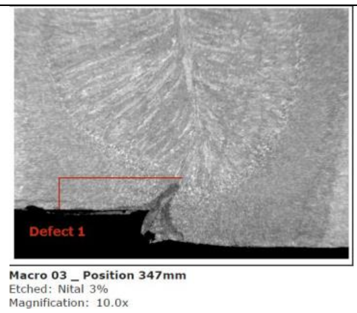
SAMPLE 2					
Flaw description	**EMAT indication (Figure 8)**	**EMAT length estim. [mm]**	**RT length estim. [mm]**	**Macro section**	**Macro length estim. [mm]**
Arc-strike bevel mark	1	100	Not detected	M4	50
Sidewall LoF	2	85	64	-	-
Pipe imperfection +Arc-strike bevel mark	3	55	Not detected	M5	35
LoF	4	50	53	-	-
Sidewall LoF	5	35	Not detected	M6	20
Porosity Cluster	6	70	47	-	-
LoF	7	95	50	-	-

Figure 10: Sample 2: (ASTM A694/DNV MWP 450 grade OD 14” x 24 + 3mm WT–V30°) EMAT, RT and macro sectioning results comparison

The DT results showed that the mismatch between the EMAT and Radiographic results are due to either the tendency of oversizing showed on the EMAT inspection or the RT missed to detect areas containing lack of fusion.

SAMPLE 1		
M1	3	4





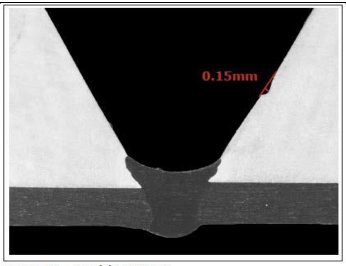
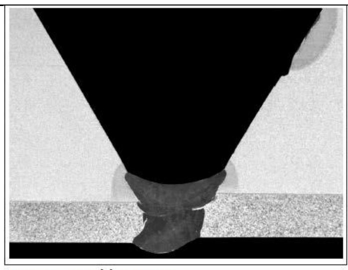
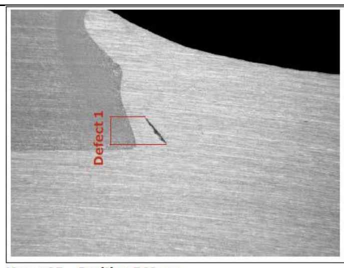
SAMPLE 2		
M4	M5	M6
 Macro 01 _ Position 70mm Etched: Nital 3% Magnification: 3.0x	 Macro 03 _ Position 280mm Etched: Chromic acid electrolytic 10% + Nital 3% Magnification: 3.0x	 Macro 05 _ Position 560mm Etched: Nital 3% Magnification: 10.0x

Figure 11: Micrographic images from the conflictive areas

5. Conclusions

All tests achieved satisfactory results, as EMAT system demonstrated a detectability equivalent to or better than radiography. The EMAT proved that it can detect lack of fusion during the hot pass where the intermediate radiography failed to detect this defect.

On the other hand, the proposed EMAT configuration has a tendency to overestimate the lengths of the defects. A general +20mm sizing inaccuracy was found with regards to the macro-sectioned indications. This effect could be due to the beam spread of the ultrasonic energy as EMAT sensors tend to be wide in size.

These results provide good confidence on the feasibility of EMAT inspection for welding process control and offer a perspective to complement or replace the intermediate radiography.

6. References

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