

Weld defect detection using PPM EMAT generated shear horizontal ultrasound

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ABSTRACT

Austenitic welds are inspected using PPM EMAT generated shear horizontal (SH) waves. Results are compared to measurements taken using a 1D piezoelectric phased array using the total focusing method (TFM). For the first time there is clear experimental evidence of the SH wave method demonstrating higher sensitivity to defect detection. SH waves suffer less beam steering in a weld than either compression or SV waves, which can miss defects due to weld microstructure anisotropy and attenuation. All defects were identified from every side of the weld/plate using the SH waves, but this was not possible using the piezoelectric transducer.

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1. Introduction

The welding process has the potential to introduce many different defects into a component [1], and as a consequence, weld inspection is a major application of non-destructive testing (NDT). Welded areas can be difficult to inspect, due to the access challenges caused by the presence of a weld cap, and in austenitic welds particularly, the highly anisotropic and attenuating nature of the weld region. There are added complications arising from the heat-affected zone (HAZ), and the many different forms that weld defects can take. This work describes a method of using shear horizontal (SH) ultrasound waves, generated and detected by periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMATs), to detect and laterally size defects within a stainless steel plate weld. This method will be compared to the performance of a piezoelectric phased array operating in full matrix capture (FMC) mode, with signals processed using the total focusing method (TFM).

1.1. Weld defects

Cracking can occur during and after the welding process. For example, if there has been insufficient weld liquid flow, or if there are high strains on the solidifying weld pool, solidification/hot cracking can occur. Fusion welding between two similar metals creates a heat-affected zone (HAZ), which has its material

properties changed (relative to the parent material) during the weld without being melted itself [1]. After the weld has been completed, residual stresses between the base material and the weld (the molten weld contracting always causes residual stresses [1]), combined with hydrogen diffusing into the HAZ, can lead to hydrogen induced HAZ cold cracking. Other defects that can occur during fusion welding include the formation of porosity or cavities due to gas or shrinkage (into which gas can diffuse), solid inclusions (such as non-metallic slag, flux, and oxides, as well as metallic copper and tungsten), lack of fusion (the weld bead adheres poorly to the base metal), incomplete penetration (the weld bead does not reach the root of the weld region), and imperfect shape such as an undercut [2–4]. A welded component subjected to fatigue loads can develop fatigue cracks in joints, which will subsequently propagate under further loading [1].

Ultrasound has been used extensively for the inspection of welds. Time of flight diffraction (TOFD) is an ultrasound technique developed for the NDT of nuclear power plants [5–7], and it has been used for general weld inspection [4]. Standard inspections may use a normal incidence compression wave transducer to check the HAZ for laminar defects, followed by an angle incidence transducer for defects in the weld itself (requiring a reflection, or skip, off the back-wall, before reaching the weld region). The use of several different transducers, covering a range of incident angles, may be required to detect some defects, and there are variations on this method that use phased arrays, allowing the incident angle to be easily changed. As well as conventional piezoelectric transducer systems, the use of EMATs for weld inspection has also been considered. EMATs producing compression or shear vertical (SV) waves can have insufficient sensitivity to detect the very low amplitude signals scattered by weld defects, and this has led to the

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creation of hybrid laser-EMAT systems for ultrasonic weld inspection [8,9]. However, this approach does not overcome issues with weld microstructure anisotropy.

Austenitic welds have a large oriented grain structure, and this causes an ultrasound beam to skew and be strongly attenuated (via scattering and absorption). The details of how the beams are skewed and attenuated are dependent on the sample (particularly the weld) and the inspection method used, but in general, SV ultrasound waves suffer from the effects of skew and attenuation to a greater extent than compression waves [10]. However, these issues are still present for compression waves, and there are additional problems such as mode-conversion from compression to SV waves.

1.2. Shear horizontal ultrasound waves

Shear horizontal (SH) ultrasound waves are guided waves (they have propagation properties affected by the geometry of the propagation medium), with symmetric and anti-symmetric modes; phase and group speeds are dependent on frequency, sample thickness, and the bulk shear wave speed [11,12]. The properties of the different modes can be very useful, such as in thickness measurement [13], but in this case they are a complication. SH0 has a thickness independent speed, equal to the shear wave speed, and is non-dispersive (the phase and group speed are equal to the shear wave speed for all frequencies). The oscillation direction of SH ultrasound is in the plane of the surface where the wave was generated, and perpendicular to the propagation direction, as shown in Fig. 1, with respect to a reference interface, which is typically a sample surface. Under certain conditions, such as over short propagation distances, SH waves can be treated as bulk waves.

Compared to compression or SV ultrasonic waves, SH waves polarised parallel to the direction of an austenitic weld will propagate through with less reflection, beam steering, and attenuation, and will not mode-convert upon interaction with a defect in the weld that extends parallel to the welding direction [14,10]. This potentially increased sensitivity to defects makes SH waves a good candidate for ultrasonically inspecting welds.

1.3. Periodic-permanent-magnet electromagnetic acoustic transducers

Periodic-permanent-magnet electromagnetic acoustic transducers (PPM EMATs) can be used to generate and detect SH ultrasound waves [15–17]. EMATs are extensively used in NDT, and their operating principles are well covered in the existing literature [18–25]. PPM EMATs have a series of permanent magnets with periodically alternating north and south (N/S) poles, which sets the primary wavelength of the ultrasound generated. A coil of

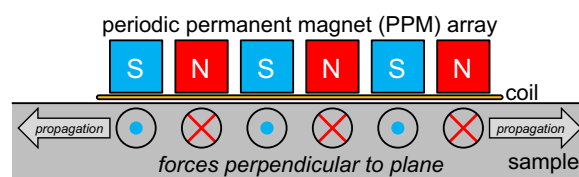


Fig. 2. Side view of a PPM EMAT for generation and detection of SH ultrasound waves. The magnets have alternating polarisation, and when a current is pulsed through the coil, periodic forces are generated in the conducting sample. The periodic magnet spacing sets the wavelength of the SH waves.

wire runs in the direction of the alternation, and when current is pulsed through the coil, eddy currents are created in the sample, that lead to a Lorentz force perpendicular to the wire direction and parallel to the surface plane [15,26,25,27], as shown in Fig. 2. These Lorentz forces generate the SH wave in the sample. For conditions under which the SH wave can be treated as a bulk wave, the propagation angle of a PPM EMAT can be varied by using the pulse frequency [28,29,27] (this cannot be done with SV waves as they do not satisfy the free-surface boundary conditions [15]), but this is not exploited in this work.

1.4. Weld inspection using PPM EMATs

The properties of SH waves make them suitable for weld inspection, but EMATs can suffer from a low signal-to-noise ratio (SNR), which favours piezoelectric transducers and hence compression waves. Relative to a metal like aluminium, steel has a lower electrical conductivity, higher density, and higher attenuation, all of which reduce EMAT efficiency [30], but with appropriate electronics and signal processing, this problem can be overcome. Investigations using SH waves on weld defects have previously used EMAT arrays [31–34] and PPM EMATs [31,35] and both have been shown to work successfully. PPM EMATs, compared to EMAT arrays, are easy to construct with a fundamental wavelength of choice, are simpler to drive (only a standard EMAT pulser is required, not a driver for an array), and only a single digitiser is required for detection, not an array. EMATs generally do not need to be profile matched, and can work on rough surfaces, but the alternating magnetic field of PPM EMATs does require close proximity to the sample surface. The maximum lift-off is dependent on the details of the sample (material and dimensions) and EMAT design, particularly the magnet width (2.5 mm magnet width for a 6 mm wavelength PPM EMAT for example), but less than 1 mm lift-off from the surface is advised, and within this study the EMATs were in contact with the sample.

1.5. Full matrix capture and the total focusing method

Full matrix capture (FMC) and the total focusing method (TFM) are used in this work as a comparison, and as such, they are briefly described here, and in detail within the literature [36].

FMC is simply the collection of time-domain data for all possible array element combinations within the phased array; the first array element is pulsed, and the scattered waves are recorded from all array elements and stored separately (pulse on element 1, receive on elements 1–64 if there are 64 elements). Next, the second array element is pulsed, and again, all array elements record the scattered waves (pulse on element 2, receive on elements 1–64). This is repeated by pulsing all remaining array elements in turn, and receiving on all array elements for each. The axes of the data matrix are then generation element, detection element, and time, with each data point representing an instantaneous amplitude [36].

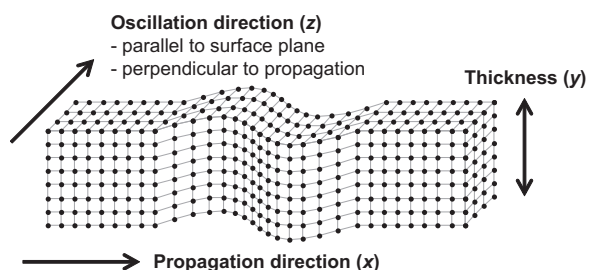


Fig. 1. A simple diagram of a SH ultrasound wave; the scale of the displacements is greatly exaggerated. Oscillation direction is parallel to the surface plane, and perpendicular to the propagation direction. As depicted here, the SH displacement is constant along the thickness direction, but this is only the case for the SH0 guided mode.

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