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Dual EMAT and PEC non-contact probe: applications to defect testing

R.S. Edwards[a,*], A. Sophian[b], S. Dixon[a], G.-Y. Tian[b], X. Jian[a]

[a]*Department of Physics, University of Warwick, Coventry CV4 7AL, UK*
[b]*School of Computing and Engineering, University of Huddersfield, Huddersfield HD1 3DH, UK*

Received 9 May 2005; revised 3 June 2005; accepted 3 June 2005
Available online 27 July 2005

Abstract

For many non-destructive testing (NDT) applications, more information and greater reliability can be gained by using different techniques for defect detection, especially when the methods are particularly sensitive to different types of defects. However, this will often lead to a much longer and more expensive test and is not always practical due to time and cost constraints. We have previously discussed initial experiments using a new dual-probe combining electromagnetic acoustic transducers (EMATs) generating and detecting ultrasonic surface waves, and a pulsed eddy current (PEC) sensor [1]. This enables more reliable detection and sizing of surface and near-surface defects, with a reduced testing time compared to using two NDT techniques separately. In this paper, we present experiments using the dual-probe on samples which are more representative of real defects, for example testing for surface defects in rails. Several aluminium calibration samples containing closely spaced and angled slots have been measured, in addition to rail samples containing manufactured and real defects. The benefits of using the dual-probe are discussed.
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Keywords: Defect detection; Ultrasound; EMAT; Eddy current NDT; Sensor fusion

1. Introduction

There is a need for increased reliability in non-destructive testing (NDT), but the cost and speed of testing remains an important issue [2,3,4]. The reliability of detecting defects in a particular sample can be increased by using several different NDT techniques, especially when one technique is sensitive to a particular kind of defect which may be present. For example, detecting gauge corner cracking in rails can be done more reliably using methods designed to be sensitive to surface defects, and combined with results from a technique sensitive to defects in the bulk of the rail will give a measure of the whole rail [3,4]. However, such in-depth testing would take an increased length of time and this is often unacceptable in terms of speed and cost, especially in an on-line environment. Because of this, only one technique is normally used, and it is accepted that this will have a lower reliability than if two techniques were used.

A probe combining several different measurement instruments would have many advantages, in particular the increased reliability from using several techniques with the testing speed of using only one probe [5]. Production costs could be reduced and some of the hardware and the analysis software could be combined in one PC. When combining complementary techniques data fusion is possible, and hence an even greater accuracy is possible [6].

We have combined two techniques that are sensitive to surface and subsurface defects into a single probe; pulsed eddy current (PEC) [7,8], and ultrasonic measurements using low-frequency broadband surface waves generated and detected using two electro-magnetic acoustic transducers (EMATs) [9–12]. By using these techniques together we are able to accurately characterise surface breaking defects with depths of up to 20 mm, with the PEC being more sensitive to shallower surface cracks with a main sensitivity to defects of up to 5 mm deep, and the EMATs being more sensitive to surface breaking defects with depths of between 2.5 and 15 mm deep [1,7,8,10–13]. In the depth region where both techniques show good accuracy, combining the results will give a more reliable depth measurement. In the aluminium calibration samples used, experimental errors in the ultrasonic depth measurements

* Tel.: +44 2476 574116; fax: +44 2476 692016.
E-mail address: r.s.edwards@warwick.ac.uk (R.S. Edwards).

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doi:10.1016/j.ndteint.2005.06.001

are around 4% for slot depths between 2 and 15 mm and are less than 2% for the PEC measurements for slot depths between 1 and 10 mm.

Both techniques are non-contact, enabling them to work at a small standoff set by the user, typically around 1.5 mm [7,8,10,12,14,15]. Their non-contact nature means that in on-line applications they are simpler to set-up and use, especially where there may be corrosion on the surface, or where weld caps need to be avoided, or where the test sample is moving [3,4]. Current ultrasonic rail testing requires a couplant and constant contact with the rail, and so removing these needs is advantageous [3].

We have recently reported initial measurements using the dual probe on two aluminium calibration samples containing slots of different depths and subsurface holes machined parallel to the faces, and a steel sample with a machined slot [1]. The presence of the magnets in the particular arrangement of EMATs used enhances the PEC signal on magnetic samples, and no other interference between the two techniques is observed.

2. Experimental set-up

A dual probe containing a PEC sensor and two EMATs (a generator and a detector) has been designed and is shown in Fig. 1 [1]. The EMATs are held at either end of the probe in a ‘pitch-catch’ mode, where one EMAT generates the ultrasound and the second detects the ultrasound a fixed distance away. In the centre of the probe there is a threaded hole for positioning the PEC sensor. The probe sits in a trolley, which enables it to be moved along the sample surface at a constant standoff.

An EMAT–EMAT separation of 150 mm was chosen as it separates the Rayleigh wave in time from the electronic dead-time following the generation EMAT current pulse, and was an initial estimate of the distance between the EMATs and the PEC sensor for minimising interference. Recent experiments have shown that smaller separations are also possible without interference [1]. The trolley and probe have been designed such that the EMATs may be replaced with improved designs or laser generation or detection, and the PEC can be replaced with other techniques such as pulsed magnetic flux leakage (PMFL) when needed. This configuration of EMATs and PEC is good for relatively flat samples where defects will always appear within the area tested by the probe. However, for larger samples and curved samples such as rails it is intended that an array of probes would be used [4,14].

Two PEC probes with different diameters are used in these experiments. The smaller probe with a multilayered cylindrical coil of 40 turns with ID of 7 mm, OD of 9 mm, and height of 0.5 mm was designed mainly for surface crack detection. The other probe has a coil of 150 turns with ID of 17 mm, OD of 24 mm, and height of 4 mm and is more sensitive to defects located deeper below the surface. The coils are used to excite a varying magnetic field which in turn induces an eddy current in the test sample. A rectangular waveform is used with a pulse width of 5 ms for the field excitation. The use of a rectangular waveform

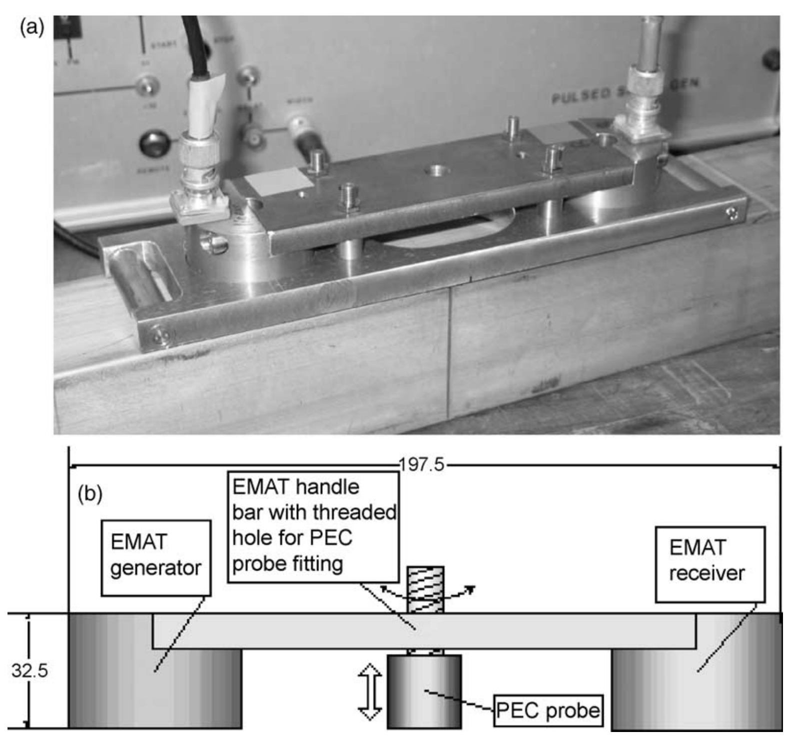
(a)


Fig. 1. (a) The trolley holding part of the dual probe with the EMATs at either end and the PEC probe to be connected to the central hole. Standoff can be changed by inserting spacers onto the four legs. (b) Schematic diagram.

instead of a sinusoidal waveform leads to a richness of excitation field frequencies allowing more information on defect depth to be obtained [7,8]. A solid-state GMR sensor is used to measure the magnetic field intensity above the inspected surface. Good sensitivity of the magnetic sensor to frequencies down to 0 Hz makes deeper inspection into the test sample possible.

EMATs couple to electrically conducting samples via the Lorentz mechanism and to magnetic samples via a magnetoelastic mechanism. The generation EMAT consists of a coil of wire through which a current of around 300 A with a duration of about 5 μs is pulsed [10–12]. This coil is located beneath a permanent magnet with its field directed normally out of the sample. When a current is pulsed through the generating EMAT a mirror current is generated within the sample skin depth in opposition to the generating pulse, and a Lorentz force is experienced by the conduction electrons. This moves the atoms slightly and an ultrasound pulse is generated. In magnetic materials ultrasound can also be generated by magnetostriction [11,12]. The detection EMAT is a coil of 25 turns of 0.08 mm diameter wire wound around a similar magnet to produce a linear coil. Standoffs of up to 5 mm above aluminium samples are possible, but for these experiments standoffs of 1.5 mm are used in order to have a good signal to noise ratio [9,15].

In order to detect surface and subsurface defects we use coils designed to generate primarily low-frequency broadband Rayleigh waves on flat samples, which are able to probe to a depth of up to 20 mm [13]. The frequency content of the ultrasound pulses is centred near 200 kHz with a width of around 300 kHz. Different designs of generation coil can be used dependent on the application. For example, some coil designs give a large amplitude signal with narrower frequency content, whereas other coils may generate lower amplitude, more wideband signal. The meander coil design of EMAT used in most of the experiments reported here gives a highly directional signal, which is beneficial for reducing reflections from sample edges and gives a high amplitude signal, but has a narrower frequency content than a linear generation coil [10–12].

2.1. Aluminium samples

We have reported experiments on aluminium calibration samples with slots machined perpendicular to the surface with a large separation from other slots or the ends of the sample to limit ultrasound reflections [1]. Using this sample the response of the dual-probe to surface breaking defects of different depths has been calibrated, and this is used when investigating real defects. In this paper we report experiments on samples which have been designed to represent more realistic defects such as those experienced in on-line applications [4,16]. The first sample contains closely spaced slots machined in pairs along two faces of a long aluminium bar at separations of 5, 10 and 20 mm, with one set of slots having both slots machined to a depth of 5 mm, and the other set of slots having one slot machined to 5 mm and the other to a depth of 2.5 mm. The second sample has slots machined at an angle to the surface normal; this was intended to simulate the angled defects found in gauge corner cracking. Slots with their tips 5 mm normally below the sample surface and machined at angles 22.5, 45 and 67.5° to the surface normal were used. Other slots in this sample inclined at 45° to the surface normal have tip depths of 1, 2.5 and 10 mm.

2.2. Steel samples

Further experiments were performed on rail samples to test that the method is applicable to curved and steel samples. In a curved railhead sample the ultrasound generated is a guided wave with properties similar to those of a Rayleigh wave [14,17], and accurate placing of the PEC sensor is essential. The first sample studied was a section of rail initially free of defects, with a slot machined across the railhead to a depth of 4.5 mm at its deepest point (shown in Fig. 2(a)). Further rail samples with real defects developed in service were also examined and are shown in

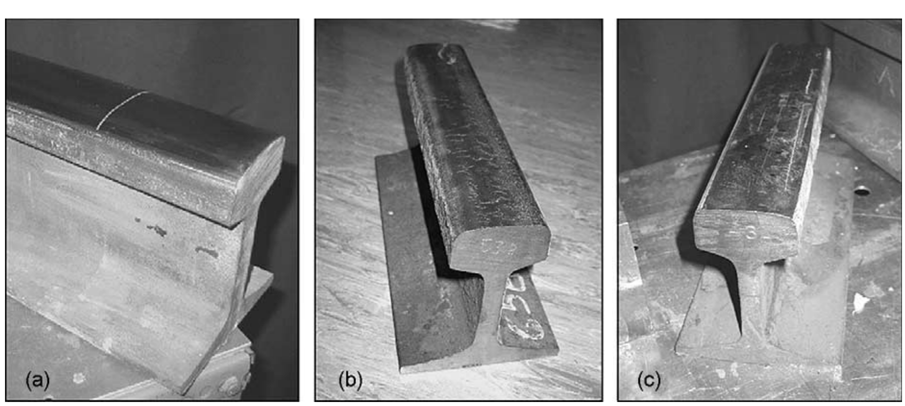


Fig. 2. Rail samples. (a) Shows the previously defect free section with a slot machined across the railhead. (b) Shows transverse surface cracking, while (c) contains a longitudinal defect.

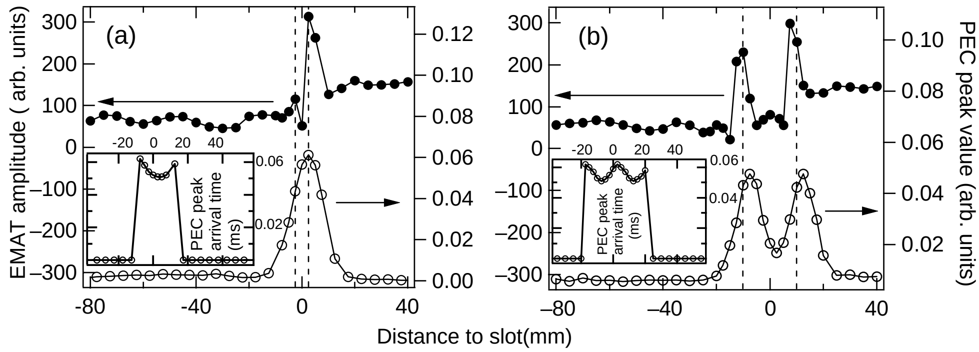


Fig. 3. EMAT signal amplitude (left axes, solid points), the PEC peak signal (right axes, open points) and the peak arrival time (insets) for slots of the same depth and (a) 5 mm or (b) 20 mm separation.

Fig. 2; these samples exhibit surface cracking (b) and longitudinal defects along the rail head (c), as well as corrosion and spalling on the surfaces [4].

3. Results

The first sample studied was the aluminium bar with closely spaced slots, with the probes scanned along the surface in 5 mm steps when far from the defect, and in smaller steps close to the defect. The Rayleigh wave signal amplitude and frequency content at the receiving EMAT, as well as the PEC peak signal and peak arrival time, were recorded [8,10].

3.1. Experimental results for aluminium samples

For the separation of EMATs used, the Rayleigh waves arrive between 50 and 60 μs after the generation current trigger pulse, and are spread out in time due to their broadband nature and the design of meander coil used. Reflections from the slot can be seen moving in time with changing receive EMAT-slot distance, and an enhancement of the signal may be observed at each slot due to interference between the signal passing directly between the EMATs and that reflected from the slots [10]. This enhancement is a characteristic feature of the presence of a defect and can be used to give an accurate location of the defect. When the receive EMAT passes over each slot a drop in signal amplitude is seen as a portion of the signal is reflected back from the slot. Once both EMATs are on the same side of the slots the signal returns to its previous strength.

Results showing the peak to peak ultrasonic amplitude (left axes, solid points), the PEC signal's peak value (right axes, open points) and arrival times in ms for the PEC peaks (insets) are shown in Figs. 3 and 4, for several different slot combinations. Fig. 3(a) and (b) show the results for two closely spaced slots both with 5 mm depth and 5 or 20 mm separation, respectively, using the larger diameter PEC sensor. As the separation is increased the presence of two slots becomes obvious; two enhancements of the ultrasonic signal are seen (one at each slot), two PEC peaks are observed, and a double feature in the PEC arrival time is also seen for 20 mm separation.

With the bulk wave ultrasonic techniques currently used in testing for gauge corner cracking in rails, smaller cracks may mask the presence of close-by deeper, more serious, defects. Fig. 4(a) and (b) show experiments approaching first the 2.5 mm deep slot followed by the 5 mm deep slot at separations of 5 and 10 mm, using the same EMAT set-up and the small diameter PEC sensor. At a separation of 5 mm the PEC cannot distinguish between the two (Fig. 4(a)) and detects them as one wider

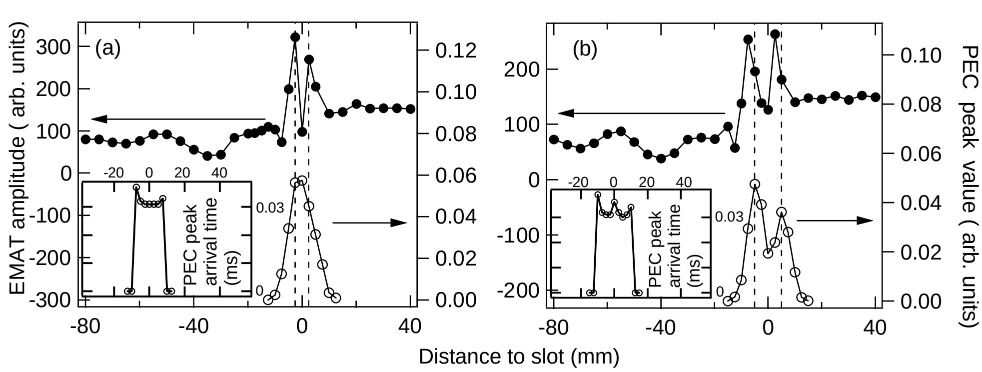


Fig. 4. As Fig. 3, for slots of different depths approaching the shallow slot first for (a) 5 mm and (b) 10 mm separations.

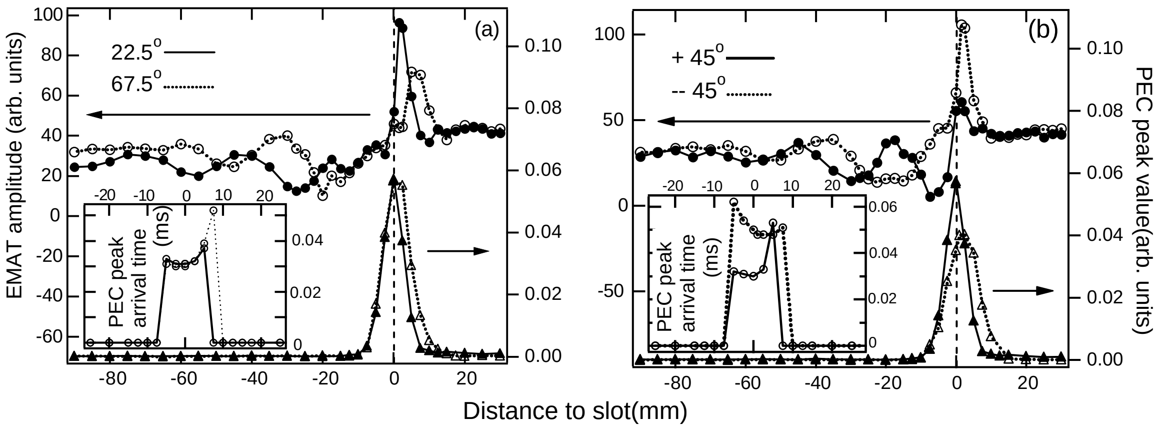


Fig. 5. Experiments on the 5 mm deep angled slots for angles of 22.5, 45, and 67.5° to the surface normal. Arrangement as in Fig. 4, with circles representing the EMAT signal amplitude and triangles the PEC peak value.

slot, however, two enhancements of the ultrasonic signal are seen for this separation and the presence of the close-by smaller crack does not mask the effects from the deeper slot. At larger separations both techniques detect the double crack. Finer detail can be resolved by using the smaller diameter PEC sensor.

It is essential to be able to gauge the depth of the slots in addition to their position, to limit the occurrence of 'false-calls' and the removal of sections of metal containing defects sized below the chosen rejection level. In Fig. 4(b) the PEC peak is lower for the 2.5 mm slot than the 5 mm deep slot, whereas they show the same peak amplitude in Fig. 3(b) for same depth slots, and this could be used to size closely spaced defects. To size defects using ultrasound the change in the transmitted signal amplitude and frequency content of the surface wave are used as the EMATs move to either side of the defect [9,12,14]. When using the EMATs in a pitch–catch manner the experimental results are dominated by the deepest slot present. The overall drop in signal amplitude as the EMATs move from one side of the slots to either side (going from positive to negative distance scale) is very similar for each case. A more reliable depth estimate comes from the changes in the frequency content [9,14].

Defects inclined at an angle to the surface are often observed, particularly in gauge corner cracking in rails [4]. The angled slot sample described above is intended to provide an initial approximate calibration for this type of defect. Again, positive distance values correspond to the EMATs on the same side of the slot opening, with the positive angles corresponding to scans where the probe runs above the tip followed by the opening of the slot, and negative angles for scans in the opposite direction.

Fig. 5 shows results on the angled slot sample. The enhancement and subsequent drop in the ultrasonic signal is dependent on the slot angle through the transmission and reflection coefficients [13,18]. The PEC measurements give a measure of the direction of the slot through the asymmetry of the peak arrival time (positive or negative angle) and the depth of the tip of the slot below the surface, but finding the angle is difficult. By combining the two measurements and with calibration of the signals we will be able to measure accurately the depth, position, angle and direction of the crack. The difference in PEC peaks between the positive and negative 45° slots is due to the use of two different diameter probes.

Fig. 6 shows results on the 45° slots of different depths. In the PEC results the peak signal is dependent on depth, with

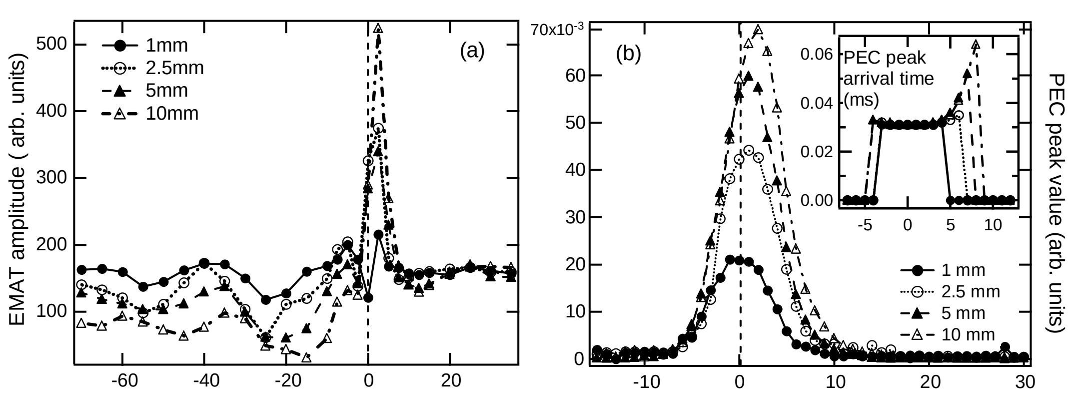


Fig. 6. The depth dependence of the signals for slots of depth 1, 2.5, 5 and 10 mm inclined at an angle of 45° to the surface normal.

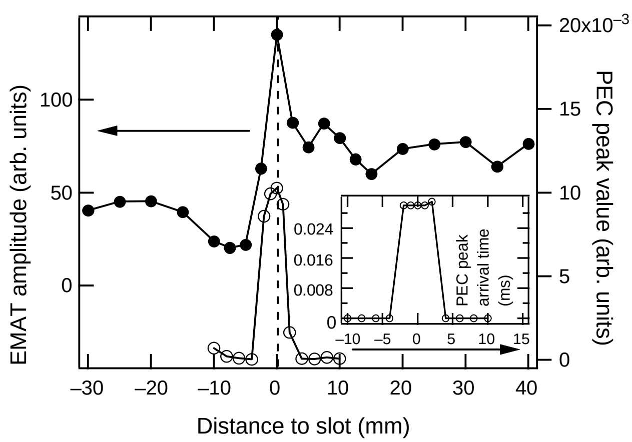


Fig. 7. Scan along the section of rail with manufactured slot, showing EMAT signal amplitude (solid points, left axis) and PEC peak signal results (open points, right axis).

the depth increase also shown in the maximum of the peak arrival time. For very shallow slots (e.g. the 1 mm deep slot) the peak arrival time looks significantly like that for a very shallow surface normal defect [1]. As the depth of the slots increase, the asymmetry of the arrival time becomes more obvious. For the ultrasonic signal the enhancement is dependent on depth, as is the cut-off in signal as the EMATs are moved to either side of each defect. It is important to measure the drop in signal when the receive EMAT is away from the slot to avoid any interference with mode-converted and diffracted waves.

3.2. Experimental results for steel samples

Fig. 7 shows results taken on the rail sample with a slot machined across the railhead to a depth of 4.5 mm at its deepest point, with the dual probe scanned along the top of the rail. Again, the position of the slot is shown by the enhancement and subsequent drop in ultrasonic signal amplitude as the EMATs move from being on the same side of the slot (positive distance) to either side (negative distance), and also by the peak in the PEC signal. These results were taken on a curved surface rather than the flat surface of the calibration samples, which shows that the dual-probe approach is applicable to rail as well as billet measurements.

Further experiments were done on the rail samples shown in Fig. 2 containing both longitudinal and transverse railhead defects. We show here that it is possible to detect and position these defects using the dual probe technique.

Fig. 8 shows results on the sample exhibiting surface cracking shown in Fig. 2(b). A full scan of the railhead using two linear coil EMATs was done, with the results shown in the B-scan; the distance from the end of the rail is shown on the y-axis, the time from the initial current pulse is shown on the x-axis, and the amplitude of the signal is shown by the brightness of the plot. The Rayleigh-like wave arrives around 65 μs (EMAT-EMAT separation is 162.5 mm).

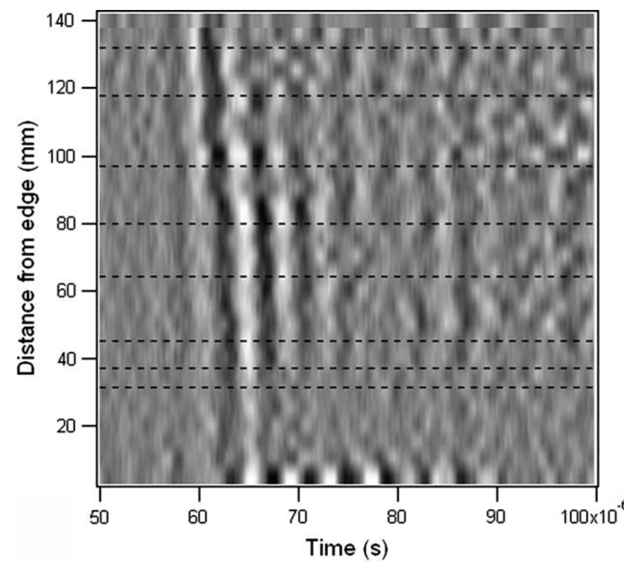


Fig. 8. Scans on the rail sample exhibiting surface cracking (Fig. 2(b)). The EMAT B-scan shows a modulation of the signal at the cracks, and crack positions from PMFL measurements are shown as dashed lines.

A modulation of the signal amplitude is seen, with sections of the plot brighter/darker than others when reflections from the cracking interfere constructively with the direct signal [10]. For steel inspection, a pulsed magnetic flux leakage (PMFL) technique-based probe can also be used in place of the PEC probe. PMFL probes consist of a U-shaped ferrite yoke with a coil wire wound on it and a magnetic sensor. More details on this technique can be found in [19]. A second scan was done separately using a PMFL probe, and the positions of the detected slots are shown as dashed lines. These agree very well with the positions of enhanced EMAT signal amplitude.

The sample shown in Fig. 2(c) has a longitudinal crack along one side of the railhead. Measurements of this type of defect would be difficult using the configuration of EMATs and PEC described earlier, as the PEC would need to be directly above the defect, and this positioning when running the probe along the railhead cuts out the ultrasonic signal almost entirely. However, by placing the EMATs on either side of the railhead and the PEC probe above the defect it is possible to measure the depth, and this is an application where arrays would be useful [14]. A spiral generation EMAT coil without a permanent magnet (this still has good generation efficiency, as discussed in reference [20]) and a linear receive EMAT as described above, held on either side of the railhead with fixed separation, were used for this experiment to make the experimental set-up as simple as possible for initial measurements. The approximate depth of the crack was measured by the change in ultrasonic signal amplitude [9,14], and is shown as solid points at eight different positions along the rail in Fig. 9. These measurements were done using an early calibration, and will be repeated using the meander generating coil and the full calibration for greater accuracy. As a comparison,

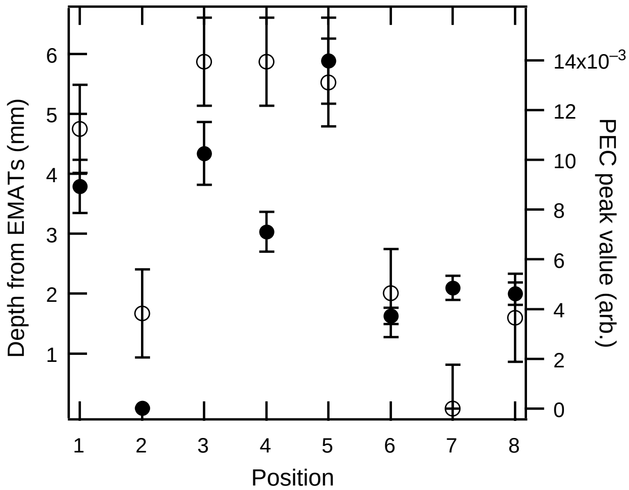


Fig. 9. Results of measurements on the rail sample with a longitudinal railhead defect as shown in Fig. 2(c). The solid points show the depths calculated by the EMAT measurements (left axis), while the open points show the PEC peak values from initial measurements.

the PEC peak value was measured at each point, and gives an approximation for the relative depths of the slots (open points).

4. Discussion and conclusions

The experiments reported previously [1] showed initial experiments using our dual-probe on well separated surface breaking and subsurface defects. In this paper we have shown that the dual-probe technique is able to detect surface breaking defects which are more representative of those experienced in applications, in particular defects which are closely spaced or inclined at an angle to the surface normal.

The two techniques combined in the dual-probe are complimentary. Both measure surface and subsurface defects, with the PEC more sensitive to shallow defects and the EMATs sensitive to surface breaking defects extending to depths of up to 20 mm below the surface, due to the use of low-frequency wideband Rayleigh waves. For different defect configurations (for example, closely spaced or angled slots) the results from each technique can be combined to provide more information than for one technique alone. With the angled slot sample, the direction of the slot relative to the scan direction is measured by the PEC peak arrival time. The angle and depth of the slot can be measured by combining the results from the PEC with the changes in signal amplitude of the Rayleigh wave, both where the signal is enhanced and where the signal is reduced when the EMATs are on either side of the defect. In this case the dual-probe approach offers a clear advantage over single techniques. More modelling and calibration work is required in order to give accurate orientations and depths of defects.

The dual-probe has been designed to be upgradeable when new and better EMAT coils and PEC sensors are designed. It has been shown by studying closely spaced slots that a smaller PEC probe will show more detail and be able to distinguish defects with less than 10 mm separation. Different techniques may be combined into the dual-probe when needed, for example PMFL on steel or rail samples instead of PEC. EMAT performance is constantly being improved, and there is space for replacing the meander coil with linear or other designs dependent on the application and the required characteristics of the ultrasound pulse. Laser generation and detection of the ultrasound are also possible by including adaptors to the dual-probe for fibre optic cables for transmission of the laser pulses [21].

In many applications where the sample surface may be curved, there was some concern over whether the dual-probe could accurately detect and size defects. It has been shown that railhead curvature does not greatly affect the results, provided that the probe is kept at a fixed orientation around the railhead so that there are no standoff changes resulting from the curvature. Both manufactured and real defects in the railhead have been measured, and reliable sizing will be possible once calibration of the dual-probe has been completed. In rail applications the EMATs will be able to quickly gauge the depth of the deepest slot in a section of rail between the EMATs and give a measure of whether the rail needs immediate replacement, with the PEC probe giving further fine details and a confirmation of the sizing of the defects.

Using PEC and EMAT together shows no detrimental interference, with the PEC signal on magnetic samples enhanced by the presence of the EMAT magnets. Using a dual-probe approach will bring many benefits, but most importantly a higher accuracy for sizing and detection of defects, with a reduced time and cost as compared to using separate NDT devices. In some situations one technique will give much improved results as compared to the other, for example, on very rough surfaces the PEC signal may suffer from a poor signal to noise ratio, whereas the low frequency Rayleigh waves used are insensitive to roughness on the millimetre scale. For partially closed cracks containing corrosion products the ultrasound may be able to partially pass through the crack due to coupling between the two sides and the defect would be missed or the depth under-estimated, whereas the PEC will not be affected by the coupling and will give much more accurate detection and depth gauging. Each technique can be used to compensate for changes which may affect the other, for example changes in lift-off or noise. This device has applications to rail testing, in particular looking for surface defects such as gauge corner cracking, checking billets for defects online, and many other situations where surface and subsurface defects may be present in metallic samples.

Acknowledgements

This work was funded by the EPSRC under grants GR/S24435/01 and GR/S24428/01.

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