Novel Multiplexed Eddy-Current Array for Surface Crack Detection on Rough Steel Surface

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Abstract. Products featuring very irregular surfaces, such as-cast slabs or billets, have remained an issue for non-destructive detection of cracks with eddy-current testing. However multiplexed arrays probes seem a promising solution to overcome the productivity/resolution challenge; they also allow easy imaging.

A specific multiplexing pattern based on transmit receive elements, which are almost insensitive to lift-off variations on normal metal allows detecting such surface-breaking flaws with little perturbations from the surface. To meet the challenge of the lift-off/resolution compromise, a special geometrical arrangement was imagined, which has to be respected. Finally multiplexing features inspection in attainable widths typically 100 mm with a 5 mm cross resolution.

We describe here the work comparing the figures of merit (resolution, lift-off) of several multiplexing patterns, with first investigations on a high surface quality finished sample with EDM notches, then on notches and apparent cracks on rough as-cast surfaces: 5 mm long cracks seem to be detectable with a 3 mm nominal stand-off.

Finally we discuss the possibilities which this new technique opens for applications in the steel industry, especially for as-cast surfaces and hot-rolled products.

Introduction

Products featuring very irregular surfaces, such as-cast slabs or billets, have remained an issue for non-destructive detection of surface cracks. Indeed, conventional differential eddy-current probes will be highly sensitive to the surface waviness, with e.g. oscillations marks up to 1 mm deep, and to the presence of residual scale. Moreover, there is a demand for a high productivity on such large surfaces, which single probes cannot challenge. Finally, the challenge is to be able to inspect the product as upstream as possible, at the exit of the caster, where product temperature may exceed 800 °C. For these reasons several attempts to inspect slab surface at the exit of the caster ended with a limited success [1-4].

As multiplexed eddy-current array probes appeared on the market just before the turn of the 20^{th} century, the challenges to meet might find a solution. Indeed, multiplexing allows imaging at high speed, and provides numerous advantages: higher productivity, easier signal interpretation enabling to link the image to the actual scanned surface, … . Moreover, the technology may benefit widely from the software imaging developments which had been made for optical and ultrasonic inspection systems.

1 Recall on eddy-current principles and figures of merit

1.1 Basic eddy-currents

The method consists in creating an electrical current density at the surface of the part to inspect (Fig.1). A surface crack will modify the surface electrical current density distribution, since it is a physical discontinuity to current circulation.

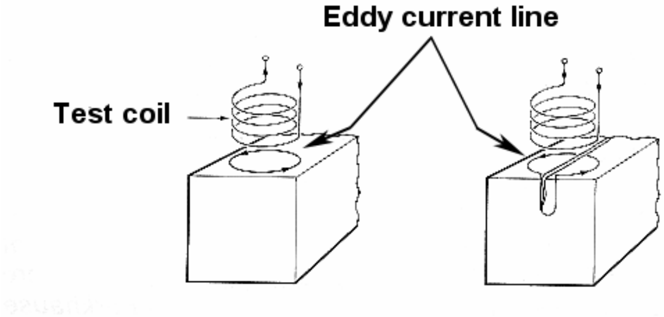

Figure 1: A surface crack will modify the surface current distribution

The eddy-current distribution is generated by driving an alternating current at a given frequency f into a sender coil. Indeed, this set-up creates a magnetic field $\vec{M}(t)$, which is variable in time, thus generating a variable magnetic flux density $\phi(t)$ in the material to inspect. According to Lenz's law, any electrically conducting material will react to the variable magnetic flux density variable in time by generating a voltage:

$$e = -\frac{d\phi}{dt}$$

This voltage induces the presence of eddy-current loops which fight against the variable magnetic field. The stationary regime from the current generation and the eddy-current reaction is then read with a pick-up coil, which produces an output voltage at the generator frequency.

The electronics associated to the coils include a sine wave generator for the sender coil, and a dual-channel demodulator. The information is displayed in an X-Y plane as impedance as shown in figure 2. Standard functions of the system are:

- Balancing, which enables to cancel the voltage of a reference operational condition; this allows choosing the origin of the impedance display as e.g. the conditions in which the coil is inspecting a healthy surface.
- Remnant display or dual-channel data acquisition.
- Gain and Rotation functions, allow to e.g. amplify the voltage of a defect signature, and set its direction onto the vertical axis of the impedance display.
- Thresholding to activate e.g. an alarm or a defect counting, depending on the customer's needs.

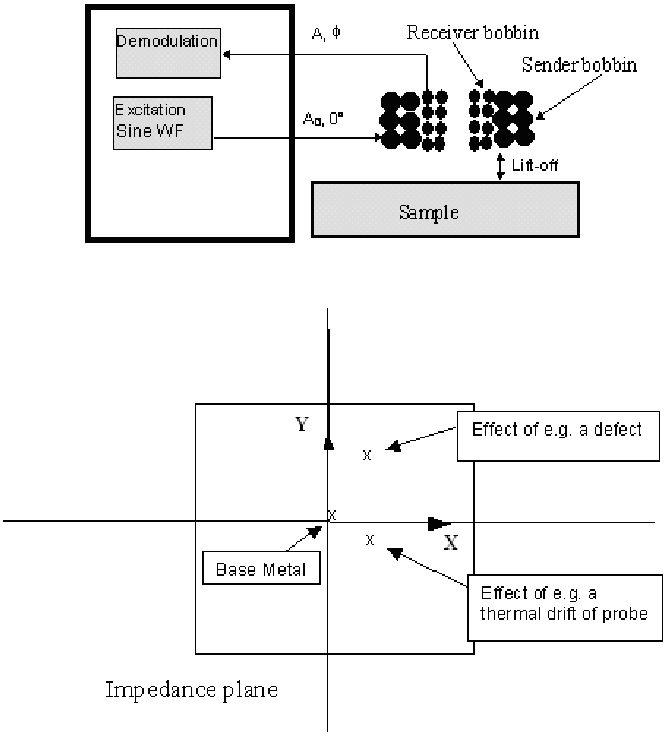

Figure 2: Eddy-current inspection schematics and impedance plane representation

1.2 Figures of merit: getting rid of perturbations

To ensure detection, the defect has to feature a signature in the impedance plane, which differs considerably from any perturbation. Such perturbations may originate from various sources:

- Variations in distance between probe and product surface
- Local presence of scale
- Local variations of coating if it is magnetic or conductive
- Local product temperature variations

Such perturbations may induce a change of the position in the impedance plane, as well as they would impact the defect signature in terms of orientation and amplitude as shown for example in figure 3.

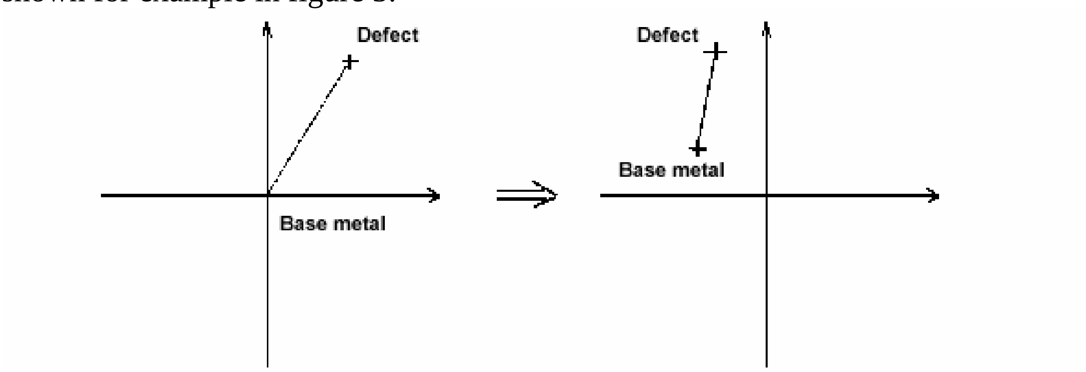

Figure 3: Effect of a perturbation on the probe signal in the impedance plane

One would ideally grade the situation on sensitivity to perturbations in the following order of preference:

- The effect of the perturbation in the impedance plane is a translation, in a direction transverse to the defect signature, without changing anything to the orientation and amplitude of defect amplitude. This situation is what the technicians in the eddy-current testing industry are usually looking for. This situation is likely to happen with temperature variations.

- Lift-off variations will induce not only a translation, but also a change in the orientation and amplitude of the defect signature. In this case it is hoped that the changes in amplitude and orientation are moderate, and the translation direction perpendicular to the defect signature.

1.3 Classical eddy-current probe testing

Common single probes such as the double D device displayed in figure 4, the detection limit and design rules of such probes obey the following general principle: if minimum defect size to detect is 4 mm, the probe diameter should be roughly equal to 4mm, and the stand-off should not exceed half of this dimension i.e. 2mm. In the case of slab surfaces with oscillation marks as deep as 1 mm, eddy-current response is likely to be very highly perturbed, leaving surface cracks virtually undetectable.

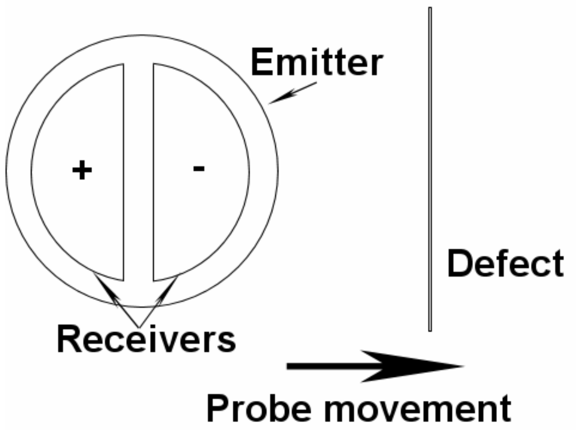

Figure 4: Differential Double D type pick-up coil

1.4 Transmit receive probes

Such probes imagined within Arcelor in the 1980's [5] use separate sender and receiver coils as displayed in figure 5. Usually these coils are co-planar, but their axes are distant. As a consequence, the receiver coil detects virtually no signal on a healthy surface. Signals will occur only when a surface crack forces the circulation of eddy-currents from the sender to the receiver.

The advantage of such a probe on very uneven as-cast surfaces can be easily explained: in the absence of a defect, the receiver gets no signal at all. Therefore the lift-off variations caused by the oscillation marks are expected to cause no signal variation on a crack-free surface. This does not however change anything to the changes in amplitude and orientation of the defect signature when the lift-off varies.

The detection limit and design rules of such probes obey the following general principle: if minimum defect size to detect is 4 mm, each probe element should be a square with size equal to 4mm, the spacing between transmitter and receiver is also 4 mm, and the maximum lift-off reaches 4 mm. Compared to a double D probe with same element size, the acceptable lift-off is multiplied by 2.

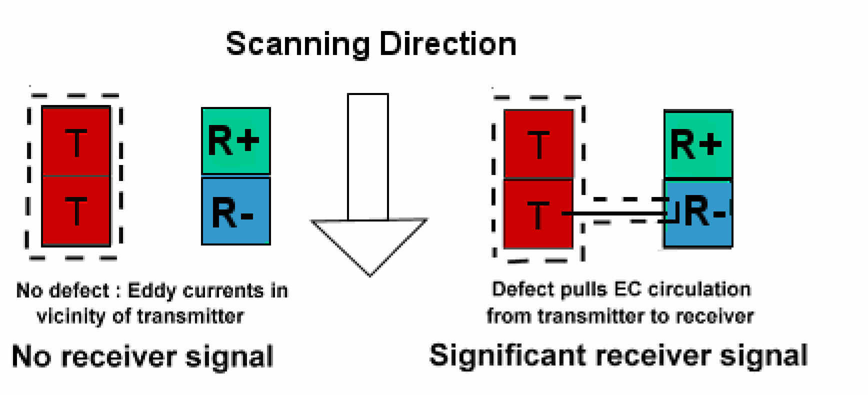

Figure 5: Transmit receive principle with 2 transmitter coils and 2 differential receiver coils

2 Multiplexed array probes

2.1 Multiplexing

Multiplexing consists in creating several time windows. During the first time window, a pattern is activated, i.e. some coils are defined as emitters and others as receivers. Emitters and receivers are chosen close enough to each other, and all the non chosen coils are in an open circuit which inhibits mutual coupling inductance problems. Then as time windows increment the pattern is shifted by one column. Figure 6 gives an example of the first four time windows, which could be used with the differential transmit receive coil shown in figure 5.

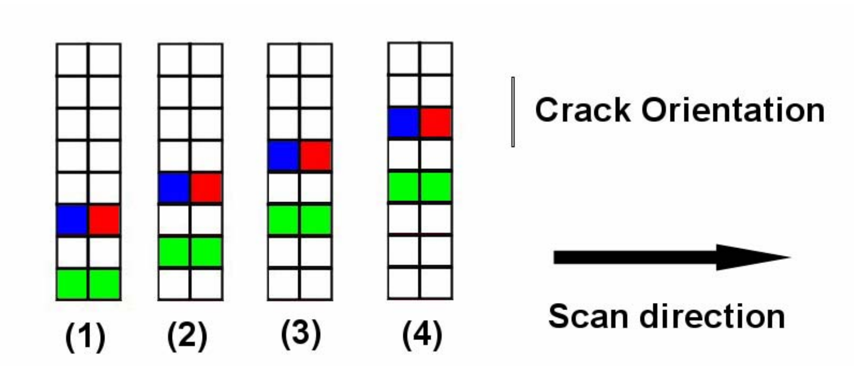

Figure 6 : First four time windows for a differential anisotropic eddy-current probe; transmitter elements are in green, differential receivers in blue and in red.

When reconstructing a differential C-scan by subtracting the signals from the blue element (negative polarization) from the red element (positive), one would expect to find an alternance of a red then a blue line while passing over a crack.

2.2 Laboratory results

All inspections used a Quickscan TC7700 with custom made probes and multiplexers from Olympus NDT (formerly RDTech). The first experiment was to have the array working at a significant distance from the surface to inspect it is necessary to design the multiplexing pattern in a way that transmitters and receivers are not adjacent, but spaced by one inactive element as shown in figure 6. This used a plate with 4 notches 1mm deep, with respective sizes of 20, 10, 5 and 2 mm. We used an array with 2 rows of 12 square elements 4.5 mm in size, as shown in figure 7.

Figure 7: 4.5 mm square element dual line array probe.

One single pass allowed detecting the notch longer than 5 mm with a nominal 3 mm lift-off as shown in figure 8. The 2 mm crack remained undetected.

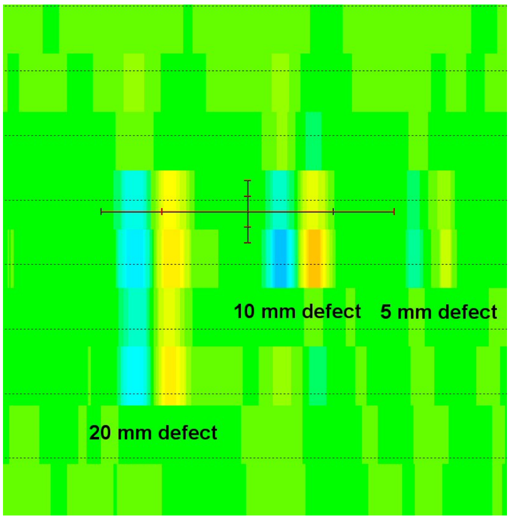

Figure 8: Detection of small cracks with a 4.5 mm square element dual line array probe, operating with 3 mm lift-off.

Moreover, the effect of lift-off variations of ± 0.5 mm has a limited impact on the impedance plane: the translations of the point representing the flawless surface are of limited amplitude, and oriented at 45° from the defect signature, as shown in figure 9. Moreover, the defect's signature remains constant despite the lift-off variations. However, such lift-off variations of ± 0.5 mm have a strong impact on the defects signature's amplitude. Bringing the lift-off from 2.5 to 3 mm almost divides the amplitude by 2, and 25% amplitude reduction is observed when the lift-off is brought from 3.0 to 3.5 mm. While still being large signal variations, one should observe that the lift-off variations on the base metal should induce very moderate signal variations compared to the notch signal itself. Therefore, the detection result was considered significantly positive for further investigation.

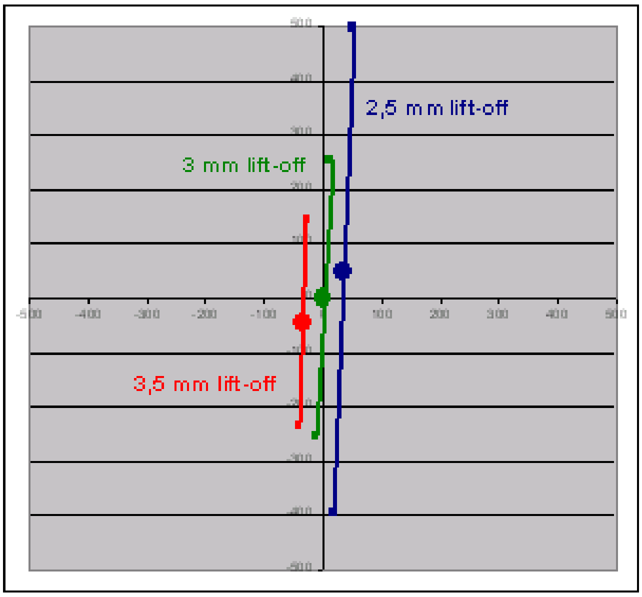

Figure 9: Effect of lift-off variations around nominal 3 mm lift-off for the 4.5 mm square element dual line array probe

Detection of a real crack

Arcelor Research was then given a selection of as cast samples, which could bear cracks. We display here the detection result we got for one of them. Figure 10 shows the detection result on the as-cast surface, without any preliminary surface treatment.

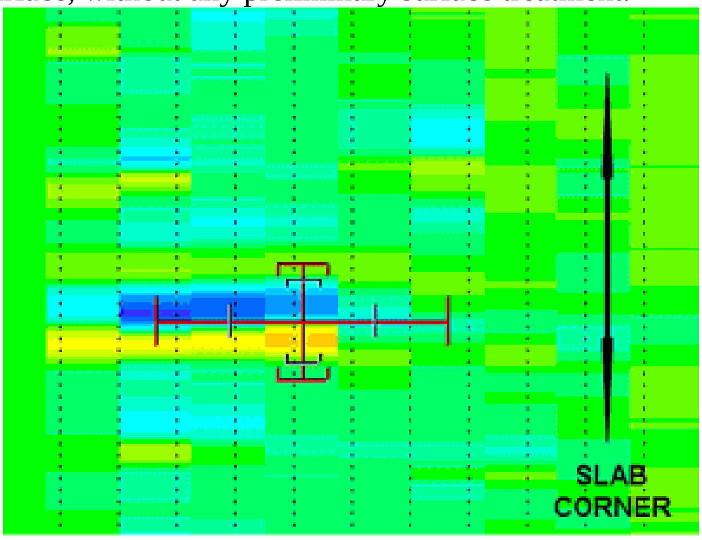

Figure 10: Probe response over a rough surface, outlining a crack. The arrow gives the position of the slab corner along the 45 mm wide C-scan. The crack is transverse to the casting direction; probe movement is also along casting direction.

It should be noted that the C-scan outlines only the detected crack, without any severe noise form the roughness of the surface, the presence of scale or the irregularity of the slab edge. The presence of the defect was immediately checked with scale removal and optical inspection under a magnifying lamp. Figure 11 gives an idea of the aspect of the crack, which was very difficult to reveal by this method.

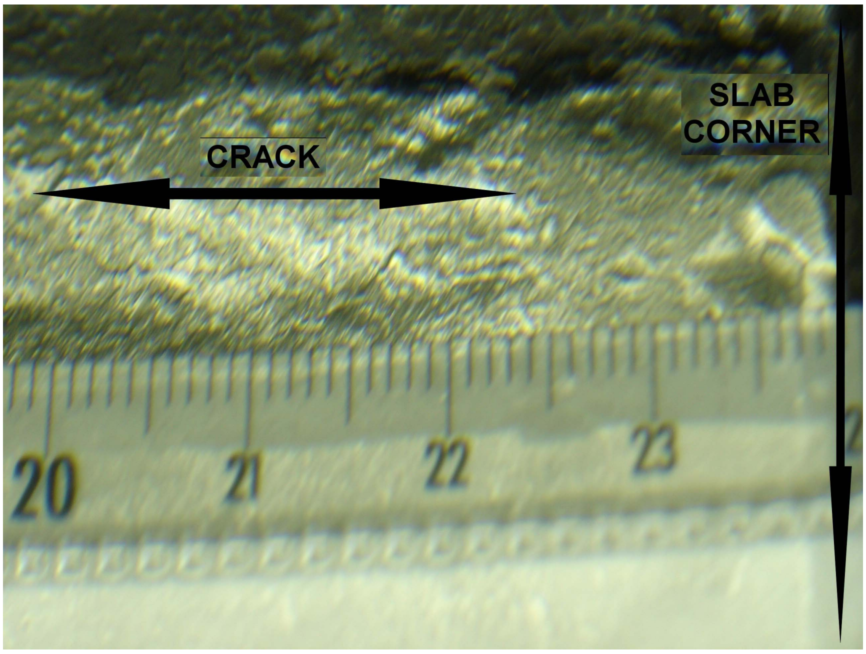

Figure 11: Crack aspect under magnifying glass. The arrow shows the slab corner.

Further investigations included a magnetic particle inspection of the test piece. Figure 12 displays 3 crack indications, instead of the single top one detected by the eddy current array probe.

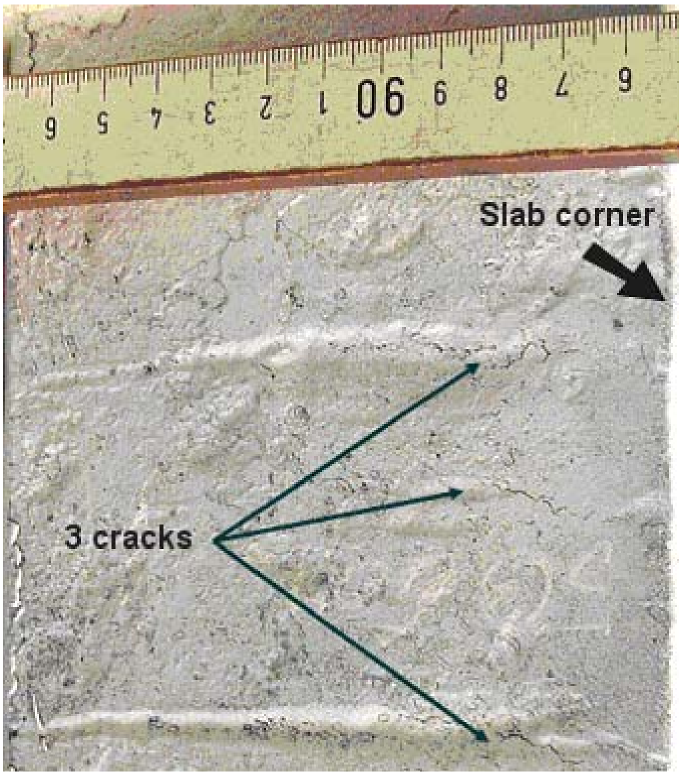

Figure 12: result of magnetic particle inspection: the crack detected with the eddy-current array probe was the top one.

There are explanations for not detecting the lower cracks. The most likely is that these cracks are very shallow, therefore not yield significant signals.

Conclusion and prospects

This novel multiplexed eddy current array probe provides very significant performance in terms of inspection of rough surfaces, especially for the detection of transverse cracks located at the slab corner:

- Cracks are detected with a stand-off of 3 mm.
- The presence of scale does not seem to hamper the defect detection
- The C-scans seem to be also immune to surface irregularities

With a system using 4 acquisition boards, each board being used for one angle, one would be able to scan 64 channels per angle. Each array requiring 2 rows with a 4.5 mm pitch, a typical scanning width would be 32 x 4.5 mm, i.e. 144 mm, which is well enough to cover the slab angle. Arcelor Research is currently coordinating European contract RFS-CR-04009 (Research Fund for Coal and Steel), involving Dillinger HW, SIDENOR and TKS, with the objective to test such a concept at the exit of a continuous caster.

Other applications may also include the detection of cracks on other as cast surfaces such as billets, or after hot rolling.

Acknowledgements

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