Implementing an ultrasonic inspection system to find surface and internal defects in hot, moving steel using EMATs

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Laser-EMAT (ElectroMagnetic Acoustic Transducer) ultrasonics is a suitable technique for on-line surface and internal defect detection in a steel mill. The system is intended to automatically inspect steel, at temperatures in excess of 700°C, as it moves through the steel manufacturing process. It is one of the few ultrasonic systems that could ever be used in the harsh operating environment of a steel mill due to its non-contact nature.

In the laboratory and pilot development stages, the equipment can be optimised and designed to work under these harsh conditions. Before the technology can be used on hot, moving product in the steel plant, it is necessary to conduct experiments on moving steel at ambient temperatures, so that system optimisation is performed under more practical conditions. As such, the design of an automated trolley inspection system for inspecting a 1.6 m-long 110 mm-square steel billet at room temperature will be discussed. The laser-EMAT system was later used to find a surface defect in the steel, as it moved at 800°C on a pilot scale rolling mill. B-scan data will be presented highlighting the presence of a surface defect on the steel moved both under laboratory and industrial conditions.

1. Introduction

There is a need to develop an automated, on-line inspection technique to examine the surface and internal quality (ie to find any defects present) in ‘as-cast’ steel products during continuous casting operations. On-line implies that the inspection system would be installed on a continuous caster as the hot steel passes a fixed inspection point. Continuous casting is the process where liquid steel is poured continuously into a mould to form the shape of slabs, blooms or billets.

The rolling process is the next stage in manufacturing and this is where as-cast products are rolled to different sizes and are worked in such a manner that they exhibit different micro/macro structural characteristics, leading to the different mechanical properties as required in the final product.

Defects in ‘as-cast’ products can be classified into two main categories – surface and internal. Surface defects include cracks, blowholes and inclusions, whilst internal defects can also include cracks, porosity, inclusions and segregation. Typical casting defects can be seen in the schematic diagram of Figure 1.

If continuous casting plant operators can be alerted, via an automated inspection facility, that the current cast of steel contains defects that are not permissible for the specific steel grade being cast, then steps can be taken to correct the problem in order to minimise any yield losses attributed to downgrading or scrapping a cast before downstream processing. The aim of current final product inspection is to ensure that no defective or ‘out-of-tolerance’ material is supplied to internal Corus Business Units or external customers as by this stage significant downstream processing has been incurred.

A laser-EMAT system has been selected as one of the few viable inspection technologies capable of inspecting both the surface and bulk of the steel. The pulsed laser beam simultaneously generates surface and bulk waves, and on samples with thicknesses comparable to the ultrasonic frequencies examined, Lamb wave modes can also be generated. The laser-EMAT system is capable of surviving the hostile environment of the continuous casting process, where some of the problems involved in installing any measurement device can include: large vibrations of the manufacturing machinery, a hot, dirty environment caused by dust in the atmosphere and iron oxide scale that can clog instruments with mechanical parts, high temperatures of up to 1000°C, steel moving at speeds between 0.5 m/s and 5 m/s and depending on the location of the sensors, significant amounts of water and steam.

Papers have been written that demonstrate laser-EMAT equipment being used to find and size defects on metal samples at room temperature. Previous work has also shown that ultrasonic measurements can be conducted at elevated temperatures. Some steel mills have conducted trials using EMAT-EMAT and laser-laser inspection techniques to find surface defects on steel, but this work has never been commercialised. Laser-EMAT technology has been used to find defects on hot, moving steel pipes and to measure the pipe wall thickness. No work has been reported to date on...
laser-EMAT technology being used to inspect ‘as-cast’ steel, when it is moving, at elevated temperatures.

As no system is currently available ‘off-the-shelf’, Corus R, D & T, in collaboration with the University of Warwick, began to develop a prototype system suitable for on-line inspection. Initial hot measurements on stationary samples heated at 800°C demonstrated that linearly wound, water-cooled EMATs could survive the hot environment and successfully detect an ultrasonic signal.

2. Method

Before the hybrid laser-EMAT system was used to inspect hot, moving steel, experiments were performed where a steel sample was moved and inspected under controlled laboratory conditions at room temperature. After this sample had been inspected, it was then heated to over 800°C and moved past the laser-EMAT system using an automated trolley system. Here, a lens is used to focus the laser beam on the steel surface.

2.1 The pulsed laser systems at Corus R, D & T

Corus has two pulsed laser systems, both capable of generating ultrasound. One laser has a pulse width of less than 10 ns, a pulse energy of 150 mJ, operates at a wavelength of 532 nm and is also portable. A second, more powerful laser system has also been used with a pulse width of less than 10 ns, a pulse energy of 800 mJ and operating at a wavelength of 1064 nm. This laser is not portable.

2.2 A LabVIEW controlled, fully automated trolley system used to detect defects in steel samples

An instrumented run-out table has been constructed and can be seen in Figure 2. This trolley system has been equipped with a motor that can move a carriage mounted with a steel sample weighing up to 250 kg. This carriage can accurately move steel samples in increments as small as 0.2 mm. The accuracy of these movements was confirmed by using a dial plunger indicator. Initialising the motor, moving to a fixed datum point and moving from the datum (zero) position to a new position can all be programmed in LabVIEW. The same LabVIEW program is configured to trigger the pulsed laser and to acquire the ultrasonic data using analogue-to-digital digitiser cards.

The EMAT is clamped in position above the steel on the trolley and remains fixed as the sample moves below it. The EMAT itself is held in place using a specially designed mechanical holder that keeps the EMAT at a near constant stand-off above the steel. This LabVIEW environment offers a high degree of automation.

3. Results

3.1 Laser-EMAT inspection of steel moving at room and elevated temperature

A 1.6 m-long 110 cm-square steel billet with a transverse defect was moved below the laser-EMAT system and inspected at room temperature for a variety of different experimental trials. After the billet was inspected at room temperature, it was heated to 800°C and inspected.

The following trials were conducted:
(i) The LabVIEW controlled trolley system moved the billet over very accurate distances, so that the entire billet could be ultrasonically inspected, in increments of 2 mm.
(ii) The trolley system was used to inspect the moving billet at a constant velocity. This measurement was taken under laboratory conditions, so that it would be possible to ascertain what to expect when the equipment was moved to the pilot scale rolling mill.
(iii) The same billet was then inspected on a pilot rolling mill where it was moved back and forth under the laser-EMAT system. This was to ensure that measurements were comparable with those listed in (i) and to ensure the equipment was ready for conducting tests when the steel was hot.
(iv) After these tests were conducted, this billet was then heated in a kiln, before being positioned on the rolling mill and moved back and forth under the laser-EMAT system. This was essentially a repeat of experiment (iii), but conducted on a heated billet.

By testing the same billet under each of these different conditions, the results can be correlated with the geometry of the experimental arrangement. By using trigonometry, it is possible to predict the arrival times of waveforms for the experimental set-up. The effect that the presence of simple geometric shaped defects will have on the waveforms can also be predicted.

A description of practical measurements and modelled predictions can be found in the following sections.

3.2 LabVIEW controlled trolley system to inspect a moving billet sample at room temperature

The billet was moved in 2 mm increments under the fixed position of the laser-EMAT system, as seen in Figure 2, and the 1064 nm wavelength laser was used for these measurements on the DLS. The relative location of ultrasonic source, detector and defect used in the experiments can be seen in Figure 3, which shows the position of the laser-EMAT system with respect to the defect. This defect was a manufactured transverse groove that was 4 mm deep and located in the middle face of the billet (the area where transverse cracking occurs most commonly).

Here, it is possible to detect the transverse defect in three different ways.

3.2.1 Case 1: The laser and EMAT are both to the right of the defect

Case 1. Laser beam and EMAT are both positioned to the right of the defect, as shown in Figure 3(a). The direct Rayleigh wave, travelling a distance ‘x’ will be detected. This wave will have a relatively large signal amplitude. Reflections from the slot will arrive progressively earlier, as the defect moves towards the EMAT. The reflected wave from the right-hand edge of the billet will take longer to reach the EMAT the further the billet moves to the right.

Because the steel can be moved incrementally in discrete steps, the data are saved after each step and averaging can also be used in these laboratory-based tests. The data are saved in binary format, as this is an efficient way to stream data rapidly to disk whilst using minimal space.

Figure 2. The billet inspected with the laser-EMAT system using the automated trolley system. Here, a lens is used to focus the laser beam on the steel surface

Figure 3(a). The direct Rayleigh wave, travelling a distance ‘x’ will be detected. This wave will have a relatively large signal amplitude. Reflections from the slot will arrive progressively earlier, as the defect moves towards the EMAT. The reflected wave from the right-hand edge of the billet will take longer to reach the EMAT the further the billet moves to the right.
3.2.2 Case 2: The laser and EMAT are separated by the defect

Case 2. The defect lies between the laser beam and the EMAT, as shown in Figure 3(b). Therefore, the direct Rayleigh wave cannot travel distance ‘x’ as the defect will at least partially block the signal. This means the wave is attenuated and will either not be detected or have a significantly smaller signal amplitude. Similarly, reflections from the edge of the billet will not be detectable.

3.2.3 Case 3: The laser and EMAT are both to the left of the defect

Case 3. This is essentially the same as Case 1, except that the laser beam and EMAT are to the left of the defect. The Rayleigh wave will have a large signal amplitude and the reflected waves from the defect and billet edge will be detectable.

Six hundred waveforms were taken at different positions as the billet was moved. At each movement step, sixteen signals were taken for averaging for this stage of the lab-based experiments. Waveform data, highlighting the appearance of the waveforms as they change through each of the Cases 1 to 3 can be seen in Figure 4. Here, p is the surface-skimming wave, r is the Rayleigh wave, ss is the shear bulk wave and r<sub>1</sub> is the reflection from the slot for Case 1.

3.3 B-scan results

Six hundred waveforms were taken at different positions as the billet was moved in 2 mm increments. The resulting B-scan can be seen in Figure 5.

Figure 5 highlights some regions of interest. Regions [a] and [b] represent the defect which attenuates the surface waves and is shown in closer detail in Figure 6. Regions [c] and [d] show the Rayleigh wave being reflected from the defect. Region [c] is r<sub>1</sub> and the reflected wave for Case 3 corresponding to Figure 3(c) can be seen in Region [d]. Regions [e] and [f] show a Rayleigh wave being reflected from the billet edge.

A magnified view of the defective area, from the B-scan in Figure 5 can be seen in Figure 6. Here, Region [a] contains two waves, [m] and [n]. [m] is a surface-skimming p wave that has mode-converted to a Rayleigh wave at the crack tip and wave [n] is a Rayleigh wave that has mode-converted to surface-skimming p-wave. Region [b] shows the drop in signal amplitude when a defect blocks the path between the laser and EMAT. There is also a delay in the arrival time of the Rayleigh wave, which can be attributed to the presence of the defect. The horizontal lines that occur at ‘length moved’ 61 cm to 62 cm, and at 69 cm can be attributed to electromagnetic noise from the motor.
Looking at the results in Figures 4 to 6, it is interesting to note that the surface-skimming and Rayleigh waves are still evident, even when the slot is blocking the path between the laser and the EMAT. This is due to some of the wideband Rayleigh wave propagating under the 4 mm deep defect. This means that not all of the surface waves are completely blocked by the defect, as it has been shown that longer wavelengths are able to pass under defects more readily than shorter wavelengths\(^{(11)}\). This was confirmed by conducting FFT analysis on the recorded Rayleigh waves.

### 3.4 Comparison with modelled results

A Finite Element Model (FEM) was constructed at Warwick University to plot B-scans. This modelled the in-plane particle velocity in steel, as would be detected by the EMAT from the Rayleigh wave generated by the pulsed laser beam ultrasonic generation source. The FEM calculates the predicted arrival times from the various wave modes and plots a B-scan. The simulated B-scan can be seen in Figure 7, which can be compared favourably to the B-scans shown in this paper that were measured experimentally.

The features in Figure 7 have been identified. Here, \([q]\) represents the Rayleigh waves as they are reflected from the defect. \([s]\) is a Rayleigh wave mode conversion to a surface-skimming p wave. \([t]\) and \([u]\) are surface-skimming p-waves that mode converted to Rayleigh waves. Again, \([m]\) is the p-wave that has mode-converted to a Rayleigh wave and \([n]\) is a r-wave that has mode-converted to a surface-skimming p-wave.

### 3.5 The trolley system used to move the billet at constant velocity

A trolley system is used to take measurements as the billet moves at constant velocity. The trolley system provides a very stable movement and was a good precursor to the measurements that would be taken on the rolling mill, where the billet would not be moved so smoothly as it passed over the roller table. Using this technique, it was possible to predict what the B-scan should look like for moving the billet on the mill. The resulting B-scan from the trolley system can be seen in Figure 8. The presence of the defect is highlighted in Regions \([a]\) and \([b]\). Region \([a]\) shows p-waves that mode converts to r-waves. Region \([b]\) shows the defect location as there is a noticeable decrease in amplitude. In addition, the defect is also detectable by looking at the r-wave reflections from the slot, as shown in Regions \([c]\) and \([d]\). These data were taken ‘single shot’, meaning that no signal averaging was performed to improve the signal-to-noise ratio hence the B-scan looks more ‘noisy’ than that of Figure 5. When the motor is energised to move the trolley system, it generates some electromagnetic noise that the EMAT picks up. This is thought to have given rise to the A-scans represented by the lines highlighted as \([f]\) and \([g]\) in the B-scan. For the B-scan shown in Figure 5, when the steel is stopped so that multiple signals can be taken at each iteration of movement, the motor is de-energised, reducing the stray electromagnetic noise detected by the EMAT. When using the motors on the pilot plant rolling mill, significantly more electromagnetic noise is generated and detected by the EMAT. Work to filter out this noise is being conducted at Warwick University.

### 3.6 Pilot rolling mill system to inspect a moving, cold billet sample

The same billet was then moved along the rolls in the rolling mill a number of times to ensure the results were repeatable using the portable 532 nm laser system to generate the ultrasonic signals.
A schematic of this equipment can be seen in Figure 9. These waveforms had a lower signal-to-noise ratio and the amplitudes of the signals were smaller than those generated by the more powerful 1064 nm laser. The resulting B-scan can be seen in Figure 10, where the defect is located in Region [a]. The mode converted Rayleigh to surface-skimming waves (and vice-versa) are barely detectable in Region [b]. It should be noted that the Rayleigh wave, as it is reflected by the defect, is just detectable, as shown in Regions [c] and [d].

3.7 Laser-EMAT inspection of steel moving at elevated temperature

3.7.1 Pilot rolling mill system to inspect a moving, hot billet sample

The same billet as described previously was heated in a furnace to 800°C at the start of the inspection process. A calibrated P60 FLIR thermal imaging camera was used to take temperature measurements as the billet was passed backwards and forwards under the laser-EMAT system. A series of ultrasonic signals were taken at different temperatures and the resulting B-scans, taken at different temperatures, were plotted.

The billet was passed through the laser-EMAT system several times. This trial was repeated by placing the billet back into the kiln and reheating it.

B-scan results taken at 800°C, on the moving billet can be seen in Figure 11.

Single shot A-scan data, taken at 800°C, can be seen in Figure 12. Figure 12 shows how the A-scans can change when a defect is present.

3.7.2 Discussion of hot trial results

It can be seen from Figures 11 and 12 that a transverse defect can be detected above the Curie point of the steel using laser-EMAT technology. None of the other ultrasonic waves, namely bulk waves that were detectable at room temperature, were easily detectable above the Curie point.

Further work is needed to improve the signal-to-noise ratio of the detected ultrasonic signals, which in turn will improve the B-scan resolution. The industrial robustness of the system is very good; the same EMAT survived the repeatable hot temperature measurements from the moving tests and suffered no noticeable deterioration in performance. A more powerful, portable laser system is also recommended. This would increase the S/N ratio of the received ultrasonic waves and could also generate bulk waves with larger amplitudes. The water-cooled EMAT holder was proven to be mechanically sound. The data acquisition systems and subsequent data analysis showed that the ultrasonic data could be converted into meaningful B-scans, utilising a high degree of automatic B-scan plotting using LabVIEW software which was then used to show the location of a defect.

4. Conclusions

An automated system for testing billets and producing B-scans, with a high degree of automation and all controlled using LabVIEW, has been designed and constructed.

The laser-EMAT equipment has successfully demonstrated the detection of a defect on hot, moving steel on a pilot scale rolling mill. Through detailed inspection of the billet at room temperature and under controlled laboratory conditions, it was possible to test the same billet on a pilot scale mill. This work is believed to be the first of its kind.

This technique continues to show much promise and the next stages in the project will involve building EMAT arrays and continuing to work on improving the signal-to-noise ratio of the equipment. A prototype system is currently being designed.
and installed for the newly constructed pilot plant continuous caster at Teesside Technology Centre, which has recently been commissioned.

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