Improved Eddy Current Sensor for Hot Wire Inspection

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Abstract. The detection of long longitudinal defects of hot wires by means of eddy current sensors is a challenge for metrology. To stabilise the sensor the lift off effect has to be controlled and reduced. Also, the sensitivity of the sensor has to be high enough to detect cracks with a depth less than 0.1 mm. This contribution will discuss the frequency response of different eddy current sensors. The results allow the definition of an optimised working point.

Different coil arrangements have been investigated. Impedance differential and emission reception modes were investigated to find the best solution for a high sensitivity and robustness. An eddy current sensor array is under development to detect long longitudinal cracks.

Introduction

The eddy current method to detect cracks is a well known technique which is widely used in industry [1, 2]. Also, examinations on hot-rolled rods can be found in literature [3, 4]. Basically one can distinguish between two different sensor types.

The first one is surrounding the sample and is suitable to detect defects perpendicular to the long axis of the sample being examined. Figure 1(a) displays the functioning of the sensor. For long longitudinal defects and defects which occur over the complete length of the sample this sensor is weak and does not give reliable results for defect detection.

The second type is a surface probe sensor which is placed onto the surface of the specimen. This sensor type is displayed in Figure 1(b). The surface probe sensor can detect long defects even such which occur over the complete length of the sample. Unfortunately, the orientation of the sensor to the defect is important to detect the wanted defects. Also an array of sensors is needed to cover e.g. the complete surface of a wire.

Within this paper encircling coils and surface probe sensors will be presented and their sensitivity will be discussed. The sensors are being developed for use within a production line within a steel plant [5]. Defect detection has to be done on materials which are up to 1000°C hot. Hence, the influence of the air gap concerning the surface probe sensor will be a topic of this work as well.
Measurement system

The measurements have been carried out according the following diagram.

A PC controlled system was used to perform the measurements. Within Agilent VEE, the x-y table was controlled as well as the Impedance Analyser. The excitation signal was generated by the Impedance Analyser and directly connected to the sensors primary side. It was also used as the reference signal to express the relationship between input and output signal of the sensor. This relationship is expressed in the unit dB.

The output signal of the sensor was connected to the Impedance Analyser also; hence the algorithm to determine the attenuation was performed within the Impedance Analyser. All measured data was saved within a file and subsequently analysed with Matlab. Sophisticated signal processing has not been performed for the data captured. This may be needed if more rough measuring conditions are encountered.

Working point of a sensor

It was found that the sensors sensitivity depends on its operating frequency. Hence, it was necessary to determine this frequency or working point of the sensor. This was accomplished by recording the attenuation between input and output signal for different frequencies. This may also be called the sensors transfer function. The working point can
be determined within air or when the sensor is placed on the specimen. For both cases no significant changes have been found. Nevertheless, it is recommended to control the working point every time when the sensor is going to be used. A typical transfer function such as for the encircling coil displayed in Figure 5 can be seen in Figure 3. The working point has been determined to be at 45 kHz.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{transfer_function.png}
\caption{Typical shape of a transfer function; measured with the sensor shown in Figure 5}
\end{figure}

\subsection*{Sensor design}

Initial measurements have been carried out with an encircling coil which had similar specifications than a commercially available coil. A sketch of the former of this encircling coil can be seen in Figure 4.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{sensor_sketch.png}
\caption{Drawing of a 4 chamber former, similar to the commercially available sensor}
\end{figure}

The four chambers are carrying four sensing coils. On top of the sensing coils an outer winding was wound which was used to generate the magnetic field within the sample. Unfortunately, the sensor did not give satisfying results for defect detection. After different variations of the physical parameters of the sensor a new improved design can be seen in Figure 5. It comprises E-cores and uses the two outer coils of the four chamber system to
generate the magnetic field within the sample. The usage of ferrites seems to be critical considering the measuring conditions of the coil. Hence, a cooling system is under development as well to ensure the ferrites are kept within their temperature range.

Figure 5: Improved encircling coil with ferrites

The surface probe sensors went through a similar process of development. First a plastic former was used but it became clear at an early stage of measurements that a ferrite core would give much better results to detect defects. Figure 6 shows two improved surface probe sensor types.

Figure 6: Improved surface probe sensor types; (a) D-coil sensor with outer excitation winding; (b) a more compact surface probe sensor

The sensor displayed in Figure 6 (a) comprises two sensing windings (D-coil shape) in the centre of the ferrite core which are connected in differential mode. The outer winding on the core is the field generating winding. On a previous developing stage the winding was placed inside the core but did not yield as good results as the arrangement shown. Within Figure 6 (b) a smaller, more compact sensor was built with slightly changed physical specifications. The D-coils have been converted into round coils wound on a small ferrite core. The field generating coil was not directly wound on a ferrite but surrounds the ferrites of the sensing coils. It was found that the latter coil arrangement gives better defect detection than the sensor displayed within Figure 6 (a).

Considering this type of sensor the orientation of the defect towards the sensing coils is important. Only when the defect ‘hits’ just one coil during the measurements it can be detected. Figure 7 shows two different possibilities a defect can encounter a surface probe sensor.
When a long longitudinal defect hits the sensor as displayed in Figure 7 a.) it will be recognised over its complete length. If it hits the sensor as displayed in part b.) only beginning and end of the defect can be detected. Hence, the orientation of the sensor on the specimen is important. To be able to detect a wide range of different defects surface probe sensors need to be arrayed. Also a combination of encircling coils and surface probe sensors should be considered.

The Spanish partners of this project also developed a surface probe sensor. An outline of the sensor can be seen in Figure 8. The sensor comprises three coils of same geometrical dimensions. One is the field generating coil and the other two work as sensing coils. Within Figure 8 a black bar indicates the location of the defect. The working principle is the same as mentioned within Figure 7. The arrow on the left side marks the moving direction of the steel.
Hence, it is important to know how the sensitivity of a sensor changes with the variation of the distance between sensor and specimen. The lift off effect is more critical for surface probe sensors than for encircling coils.

Results

A defect of 20 mm length and 1mm depth has been passed through the encircling coil with ferrites. The defect detection signal can be seen in Figure 9. The defect location is marked by the peaks within the signal at distances of 25 mm and 45 mm on the x-axis. The minimum at 45 mm has been flipped over. When the imaginary part of the signal versus real part is plotted it can be seen that there is no symmetry to the origin. As the absolute value is displayed in Figure 9 these flipping over can occur.

If a defect passes a surface probe coil as shown in Figure 7 (a) the following signal can be obtained (Figure 10). The signal while the sensor is over the defect does not return to its previous value before the defect encountered the sensor but it stays on its own level. The signal within Figure 10 has been obtained from the sensor displayed in Figure 6 (a). An output signal of the sensor displayed within Figure 6 (b) looks similar but the hub of the signal is around 10 dB whereas in the case displayed in Figure 10 it is 6 dB.
Results obtained from the surface probe sensor of the Spanish partners are displayed in Figure 11.

An overview about different specifications of the sensors can be seen within Table 1. The defect measured with the encircling coil was a longitudinal defect, parallel to the axis of the specimen.
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<td>50…500</td>
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<td>1…3</td>
<td>200…800</td>
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<tr>
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<td>Sensor Tecnatom</td>
<td>Surface probe</td>
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Table 1: Overview about different specifications of the sensors

Discussion

The signal displayed in Figure 9 clearly shows that the sensor detects the beginning and the end of a defect. The hub of a signal describes the change of the signal level when a defect is encountered. The bigger the hub is the more sensitive is the sensor. Figure 9 shows a hub of around 10 dB when the sensor hits the defect and around 26 dB when the defect leaves the sensor. So far it has not been examined fully why these different levels of change of amplitude occur. First assumptions indicate that the magnetic properties of the ferrites used to build the sensor contribute to this effect.

Figure 10 displays the signal of a surface probe sensor when the defect hits the sensor in parallel as shown in Figure 7 (a). As long as the sensor is above the defect the output signal does not return to its original value of around -38 dB. Even defects which extend over the complete length of a sample could be detected with the sensor. Unfortunately, if the defect hits the sensor perpendicular as shown in Figure 7 (b) it is not possible to detect defects which e.g. extend over the complete length of a sample. In that case the output signal is similar to the one for encircling coil as shown in Figure 9.

Figure 11 shows the output signal of the Tecnatom sensor. The defect hits one sensing coil as indicated in Figure 8 or Figure 7 (a) respectively. The sensor can detect long longitudinal defects. The hub of the signal is around 4 dB. Similar to the sensors displayed in Figure 6 it is not possible to detect defects which extend over the complete length of the sample when the defect strikes both sensing coils.
Conclusion

Different sensor types have been examined. For both categories, encircling coils and surface probe coils, it was found that the usage of ferrite materials improve the sensitivity of the sensors. Unfortunately, the ferrite materials need to be operated within their temperature range. For the tasks presented in this work a cooling system is needed to ensure that the ferrites do not heat up above their thermal operating range. Encircling coils are not suitable to detect long longitudinal defects. These types of sensors detect only start and end of a defect. Surface probe sensors can detect defects which may occur over the complete length of the specimen. But they have to be arrayed to cover the complete surface of a rod. Also the orientation of the defect to the sensing coils of a surface probe sensor is important. As long as the defect just strikes one sensing coil it will be detected.

References


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