Ultrasonic Testing of Hot Plates Using EMAT Technology

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Abstract. Ultrasonic testing of heavy plates in the hot state offers a lot of advantages compared to testing at ambient or slightly elevated temperatures. The earlier defects or abnormal properties can be detected in the production flow the more effective corrective measures such as changes of production parameters can be taken. Traditional ultrasonic inspection with piezoelectric transducers is very limited in the accessible range of temperatures. In industrial applications mostly water is used as coupling medium which limits the temperature range of the heavy plates that can be tested to between 0°C and 100°C. In contrast the EMAT (Electromagnetic Acoustical Transducer) technology is not subject to this limited temperature range. Whereas this technology applies the same methods of flaw detection the way of generating and detecting the ultrasonic waves is completely different from the traditional PET (piezoelectric transducer) technology. EMAT technology generates ultrasound directly on the surface of the test object utilising electromagnetic principles. Since there is no need to transport ultrasonic waves from the probe to the test object no coupling medium is necessary and therefore all the limitations of the temperature range are not present for the EMAT technology. The actual installations of equipment using EMAT technology for testing hot plates cover a range of upper temperatures between 150°C and 650°C. Furthermore, EMAT systems offer some more advantages compared to wet systems. Since the EMAT excites waves strictly normal to the surface of the material to be tested very stable back-wall echoes are obtained. Using the ratio between different back-wall echoes allows to detect surface cracks or defects even with straight beam transducers. Another special feature of EMAT systems is the possibility to access mechanical properties by taking advantage of the fact that shear waves typically used in applications have two main directions of polarisation which are parallel and perpendicular to the main rolling direction of the heavy plates.

Introduction

Non-destructive testing of hot material has been in practical use for many years. All over the world reliable and extremely sophisticated eddy current testing equipment is widely used at hot rolling mills all over the world. Primary goal of testing hot material is to control the production process in an early stage.
It is well known that eddy current testing detects only defects located on the surface of a test object. Consequently this test method offers no possibility to take a look inside hot material in the course of its production.
In principle X-rays and ultrasound are able to penetrate deep into a metallic test object and to detect internal defects. But many technical, economical and ecological reasons limit the application of X-rays for this purpose.
Traditional ultrasound inspection uses piezoelectric transducers to generate the ultrasound and a coupling medium between the test object and this transducer. This coupling medium

is needed to transport the ultrasound generated in the piezoelectric transducer to the object to be tested. For most industrial applications water is used as coupling medium. It is obvious that this defines the limit of the surface temperature which is around 100°C.
Until recently no reliable and sensitive solution has been available to excite and receive ultrasonic waves in hot material.
In the following most recent advances in ultrasonic testing without coupling medium will be presented. Moreover, newly developed test equipment used for the inspection of hot steel plates for internal flaws will be described.

Progress in dry ultrasonic testing

Nowadays two different kinds of ultrasonic test equipment for plates and strips are commonly used: Wet ultrasonic test equipment using piezoelectric probes and dry ultrasonic equipment using **e**lectro**m**agnetic **a**coustical **t**ransducers (EMATs).
Both types of test equipment are based on the same technique of flaw detection, contain similar components and require similar design of electronics, mechanics, control system, and software. Both are in conformity with strict modern requirements, providing the necessary sensitivity, and meeting all the international standards. The main difference between the two types of test equipment is the way of generating and receiving the ultrasonic waves.
Wet ultrasonic systems generate the ultrasound with the use of piezoelectric transducers. As a consequence a coupling medium is needed in order to transport the ultrasonic waves from the transducer into the test object. In industrial applications water is almost the only solution for plates. That restricts the range of allowable test object’s temperatures: not less than 0^oC and not more than 100^oC. Due to several practical reasons the temperature range is even smaller. Moreover, liquid coupling media like water are able to transport only longitudinal waves but no transverse or shear waves.
In contrast dry ultrasonic systems utilize EMATs to excite and receive ultrasonic oscillations. EMATs generate ultrasound directly on the surface of the test object without the need to have any mechanical contact with it. The coupling is provided by means of electromagnetic forces. As a consequence there is no ultrasound outside the test object and therefore no need for any coupling medium. Moreover, in most cases dirt, paint, or scale on the product surface do not impede testing.
In recent years the development of dry ultrasonic testing has experienced a breakthrough in technology due to several factors. Firstly, major technological improvements in electronics like powerful microprocessors and digital signal processing have to be mentioned here. Based on these improvements the development of modern software algorithms and fast data processing has become possible which is a necessary supposition to cope with the small signals typical for dry ultrasonic testing. As a second major factor the availability of new magnetic materials should be mentioned. These materials allow to build very powerful and compact electromagnetic acoustical transducers on the basis of permanent magnets instead of using big electromagnets.

Special properties and advantages of ultrasonic testing with EMAT

As a result of the different principle of generation and detection of ultrasound of EMATs compared to piezoelectric transducers several special features of the EMAT exist.
EMAT can operate in a very wide range of temperatures (- 40^oC to + 650^oC) as no restriction from any coupling medium exists. In the very common case of ferromagnetic test objects the upper limit of the temperature is determined by the Curie temperature of the material to be tested.

Another special feature based on the absence of coupling medium is that EMAT can generate and receive polarized shear waves. A polarized transversal wave is extremely sensitive to many types of natural defects including vertical cracks.
EMAT excites waves strictly normal to the surface of the material to be tested, regardless of the probe inclination. In case of flat test objects like heavy plates that involves obtaining extremely stable back-wall echoes.

Testing of steel plates early in the production flow

Some of the benefits of ultrasonic testing with EMAT directly result from the above mentioned features. To be mentioned here are the improvement of the production process, of the internal logistics and of the test quality of heavy plates. Additionally, the application of EMAT for ultrasonic testing offers the possibility to gain information about mechanical properties of the test material.

Testing of plates in a very early stage of the production process enables the operator to identify problems in the manufacturing process by the quality of the plate immediately. Therefore, corrective actions such as changes of production parameters can be initiated directly after hot rolling of the plate. No time is wasted by waiting for testing until the temperature of the plate drops below 100^{o}C. Therefore, EMAT-testing of hot material becomes a tool for process control.
In case of plates with defects decisions about further processing can already be made while the plates are still on the cooling bed as their status is already known. This can increase the output of the line. If the plates are no longer useful due to defects, they can be scrapped immediately after rolling. The potential of saving time and energy is obvious.

Improving the test quality of steel plates

Regardless of the type of transducer, scale, especially the thick and loose one, is able to create untested areas and/or generate noise, reducing reliability and sensitivity of the ultrasonic testing. For piezoelectric transducers scale can influence the shape and direction of an ultrasonic beam, and the ability of ultrasound to penetrate into the material to be tested. Materials in hot state normally do not have scale with such characteristics. According to experience for plates of above 300^{o}C no influence of scale on the ultrasonic inspection process can be observed. Therefore, the risk of having untested zones due to scale is limited in this case.
In general it is difficult to avoid untested zones along the edges of the plates. Regardless of the type of transducers applied this is a common problem for all ultrasonic test equipment.
Normally the quality of the edges is much more important than the quality of the plate body because it strongly affects the usefulness of the plate in case of welding the plate in the further process.
Therefore, to minimize or to completely avoid untested zones along the edges it is highly important to test plates before cropping. With an EMAT-system the testing process can already be accomplished long before the plate reaches the cropping station.

For several types of defects the use of shear waves has advantages compared to the use of longitudinal waves. Shear waves can detect surface defects or vertical defects that do not reflect ultrasound, but rather scatter the energy of shear (transverse) waves.

As an example figure 1 shows the A-scan of a defect-free area of a 20 mm thick plate. The x-axis gives the time scale in microseconds, while the y-axis shows the signal amplitude in dB.

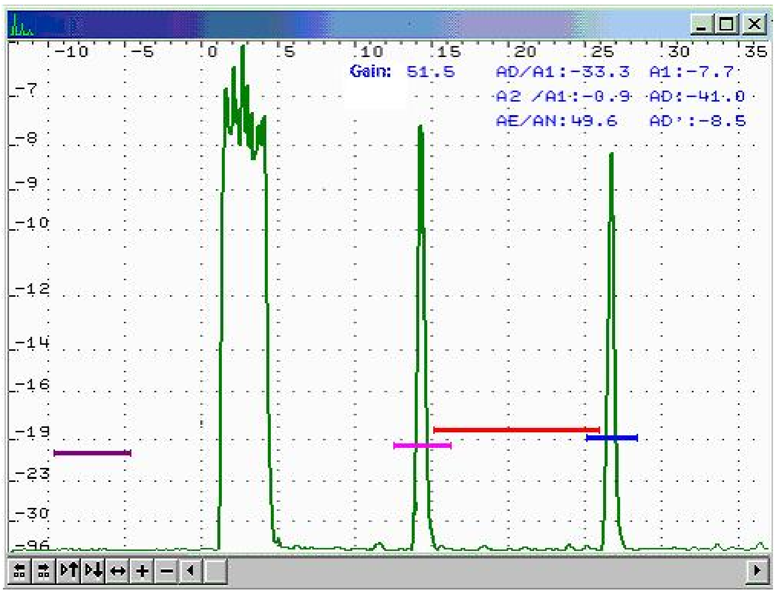

Figure 1. A-scan of a defect free area of a 20 mm plate

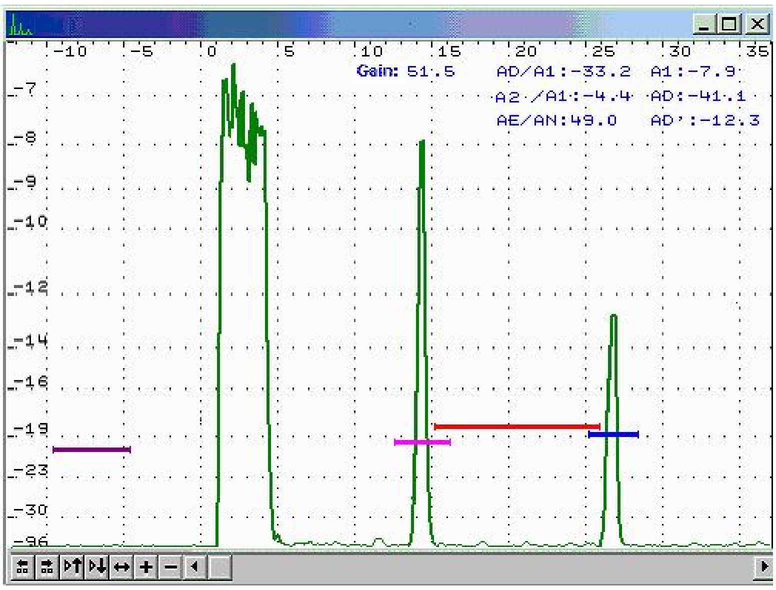

Figure 2. A-scan with an artificial scratch 0.3 mm deep in the same 20 mm plate

The red bar in the graph represents the gate AD between the first and the second back-wall echo. The magenta colored bar A1 is placed on the first back-wall echo, the blue colored bar A2 on the second back-wall echo. During the testing process the amplitudes A1 and A2 may fluctuate due to a change of the air gap between the EMAT and the surface of the plate but the difference of the amplitudes of A1 and A2 is highly constant (in case of a defect free plate). In the example shown in figure 1 the difference between A1 and A2 is only 0.9 dB. (ratio A2/A1 = -0.9 dB).

For the same plate figure 2 shows the A-scan for an area with an artificial surface scratch (notch) of 0.3 mm in depth. Due to the dead zone of the transducers near the surface such a defect can not be detected in the defect gate AD. Nevertheless, due to the presence of this surface defect the difference of amplitudes of A1 and A2 changes significantly. In figure 2 it has increased to 4.4 dB now. It should be mentioned here that this result does not allow to determine the depth of the surface defect but it can be used to detect the presence of the defect.

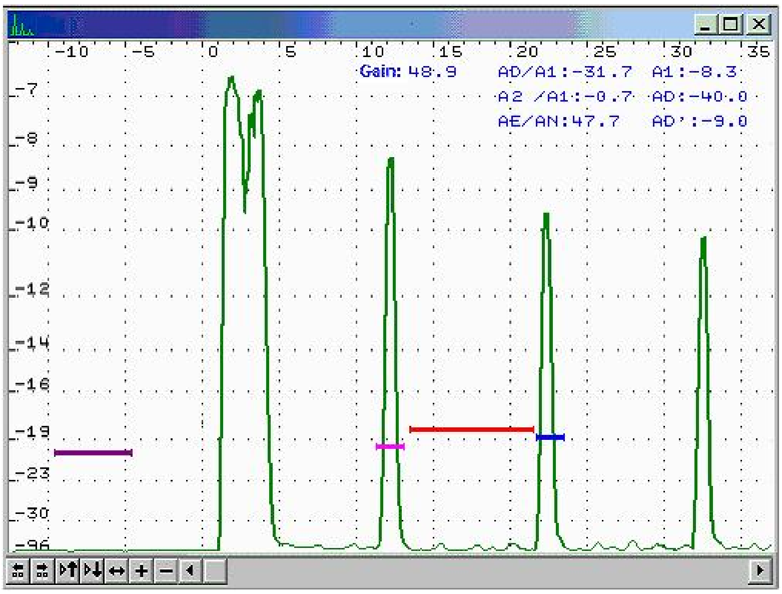

Figure 3. A-scan of a defect free area of a 16 mm plate

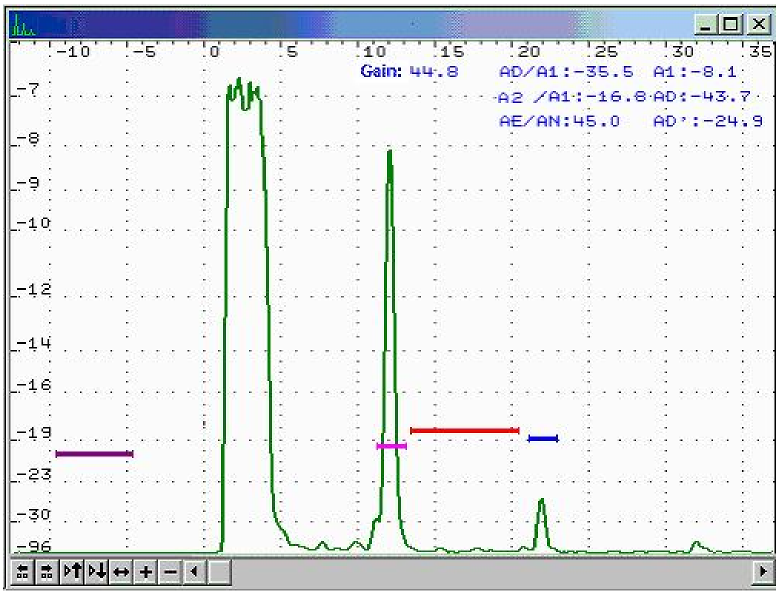

Figure4. A-scan with from the area with a natural vertical surface crack in the same 16mm plate

Another example is shown in figures 3 and 4. A polarized shear wave interacts with vertical cracks much stronger than a longitudinal one excited by a piezoelectric probe. It occurs if the crack is located mainly perpendicular to the polarization vector of the shear wave. Figure 3 shows the A-scan from a defect free area of a plate with a thickness of 16mm.

Again the difference of amplitude of the second to the first back wall echo is important. In this case it is –0.7dB. Figure 4 shows the A-scan for the same plate with a natural vertical defect. The depth of this crack is approximately 1mm. The difference in amplitudes for the second to the first back wall echo is now –16.8 dB and is the result of scattering of the wave due to the presence of the defect. Like in the example before it is not possible to make a statement about the depth of this crack but its presence can be determined.
For both examples presented above it is absolutely necessary to have a stable ratio between the amplitudes A1 and A2 of the first and the second back-wall echo. This can only be provided by EMAT but not by the conventional wet technology because in this case any small change in the angle of the probe will result in bigger changes of the ratio A1/A2 than the changes caused by surface defects.

Mechanical properties assessment

In contrast to longitudinal waves which can have only one direction of polarisation (parallel to the direction of propagation) the polarisation of shear waves can be composed of two main directions which are perpendicular to the direction of propagation. As a result, in case of heavy plate testing where the direction of propagation is typically perpendicular to the surface of the heavy plates the polarization of the shear wave can either be parallel or perpendicular to the direction of rolling. Which of these two modes are excited and with which amplitudes depends on the angle of the active zone of the EMAT-element relative to the rolling direction. In case this angle is about 45^{o} both modes of shear wave will be excited with nearly equal amplitudes. The speed of propagation of these two modes can be different which leads to an A-scan shown in figure 5.

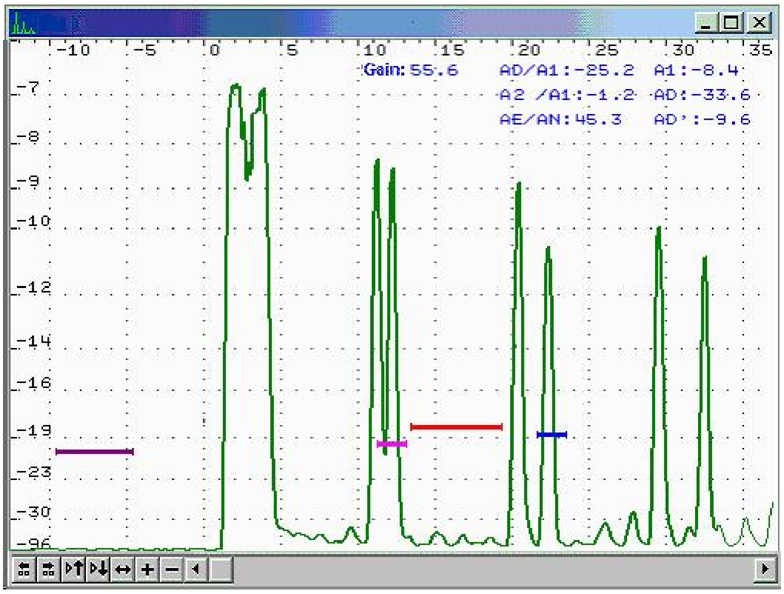

Figure 5. A-scan obtained with an EMAT turned by 45° relative to the rolling direction on a defect-free area of a 16 mm plate.

The speed of sound in steel depends on the elastic constants. Typically these elastic constants are different in the three main directions of the plate after rolling. Therefore, it is expected that the velocity of the two possible modes of a shear wave travelling perpendicular to the surface of a plate will be different. In other words the time of receiving the back wall echoes of these two modes after exciting the wave will be different. In figure 5 it can be clearly seen that the sequence of reflections of ultrasound from the walls of a

plate consists of two peaks. These reflections are the result of the two modes of shear waves propagating with different velocities, $v_\perp$ and $v_\parallel$, perpendicular and parallel to the rolling direction, respectively. The time difference increases when you go to higher orders of back wall echoes. The time difference also depends of the thickness of the plate.
The ratio of the shear wave velocities $v_\perp / v_\parallel$ defines acoustical anisotropy that directly correlates with different mechanical properties (MP) of the material. The idea is not to determine the MPs themselves, but to pay attention to all plates where the ratio $v_\perp / v_\parallel$ deviates from the typical ratio. The MP assessment can be performed by a multi-channel UT-system simultaneously with the flaw detection process. In this case active elements of every second probe should be turned by 90 degrees relative to the previous one.

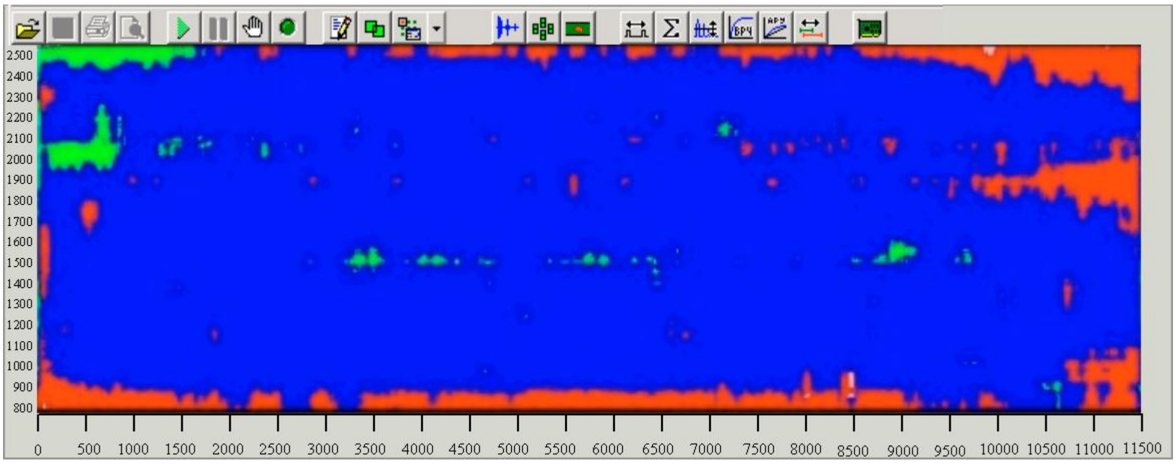

Figure 6. C-scan of a steel plate indicating areas with abnormal mechanical properties (red and green areas)

Figure 6 shows an example of a C-scan of a heavy plate indicating areas with abnormal mechanical properties. Areas shown in red colour have higher than average values of $v_\perp / v_\parallel$ while areas shown in green have lower than average values of this ratio.

EMAT testing equipment

International standards and requirements from sheet metal users become more and more uniform. Nevertheless, the actual requirements of sheet metal manufactures concerning test equipment are still extremely individual. Therefore a highly modular system like the STATOSON® F is needed. The system can be tailored to any kind of dimensions of the plates to be tested. The following table 1 shows the most common specifications.
As the quality of edges of the plates is very crucial, international standards require a far more sophisticated testing for the edges than for the plate body. Therefore, the ultrasonic test equipment is divided into two different parts: the plate body testing station and the edge testing stations.
In former years international standards required testing of the plate body without 100% coverage. The main reason was that suitable automatic testing equipment was not available. In most cases the testing was only performed in a grid like way. Today automatic testing systems allow to test with 100% coverage or even with overlap. To achieve this high density of testing transducers are mounted in a single, double, or even in three rows. Overall the STATOSON® F testing station is capable to control up to 600 channels.

Table 1. Common specifications for heavy plate testing equipment

Width	1000mm - 5000mm
Length	4000mm - 30000mm
Thickness	4mm - 200mm
Temperature	-40 °C - +650 °C
Surface	after hot rolling
Test speed	up to 2m/s

Summary

For more than five years 6 sets of dry ultrasonic testing equipment based on EMAT technology are in daily use for testing steel plates with surface temperatures of more than 100 °C at various European plants. These systems are not only used for testing purposes but also as powerful production control tools. As the requirements from all steel plants are extremely different the ultrasonic test equipment is designed highly modular. Besides finding internal defects the STATOSON® F is capable of assessing mechanical properties of plates as well as detecting some kinds of relevant surface defects.