Development and Qualification of a Process-Oriented Nondestructive Test Method for Weld Joints to Operate With Remote Field Eddy Current Technique

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Abstract. An increasing demand on high product quality and effective production processes requires process-oriented nondestructive defect detection methods.

Fundamental investigations based on the eddy current technique are presented to demonstrate the development of an innovative test method, supported by finite element method simulation. Main influence is caused by the wall thickness and the material properties of tested components. Additional influence is given by the sensor development and the adaptation of the analysis system to the testing task, including a suitable optimization of excitation currents and testing frequencies.

Using the remote field eddy current technique in practice enables both a detection of inner defects even inside thick-walled components and an inline defect detection in direct follow-up of the welding process of light metal products.

Motivation

Stronger requirements concerning the quality of thick-walled non-ferrous austenitic materials as well as light metal components, for example at the chemical, automotive and aviation industry or at manufacturing semi-finished products and profiles, increasingly demand on process-oriented nondestructive defect detection methods. These are necessary to enable qualified strategic decisions and therefore a high product quality and an effective production to avoid extra costs.

Fundamental investigations based on the eddy current technique are presented to demonstrate the development of an innovative test method, supported by finite element method simulation. Main influence is caused by the wall thickness and the material properties of tested components. Additional influence is given by the sensor development and the adaptation of the analysis system to the testing task, including a suitable optimization of excitation currents and testing frequencies.

Using the remote field eddy current technique in practice enables both a detection of inner defects even inside thick-walled components and an inline defect detection in direct follow-up of the welding process of light metal products. This meets the aim of a high geometric resolution and a significant defect sensitivity. It is possible to observe wall thicknesses that cannot be tested successfully under use of conventional eddy current systems. An analysis of a defect-caused eddy current signal within the impedance plane on the one hand leads to an evaluation of the defect type and formation concerning its dimension and orientation. On the other hand the position inside the material can be determined, e. g. root defects, defects inside the weld seam volume or the heat affected zone and defects within the welding pass.

Due to these investigation results, there are possibilities for an online control of the welding process in order to classify and to evaluate welding defects and therefore to realize a high potential quality management near to industrial production processes (figure 1).

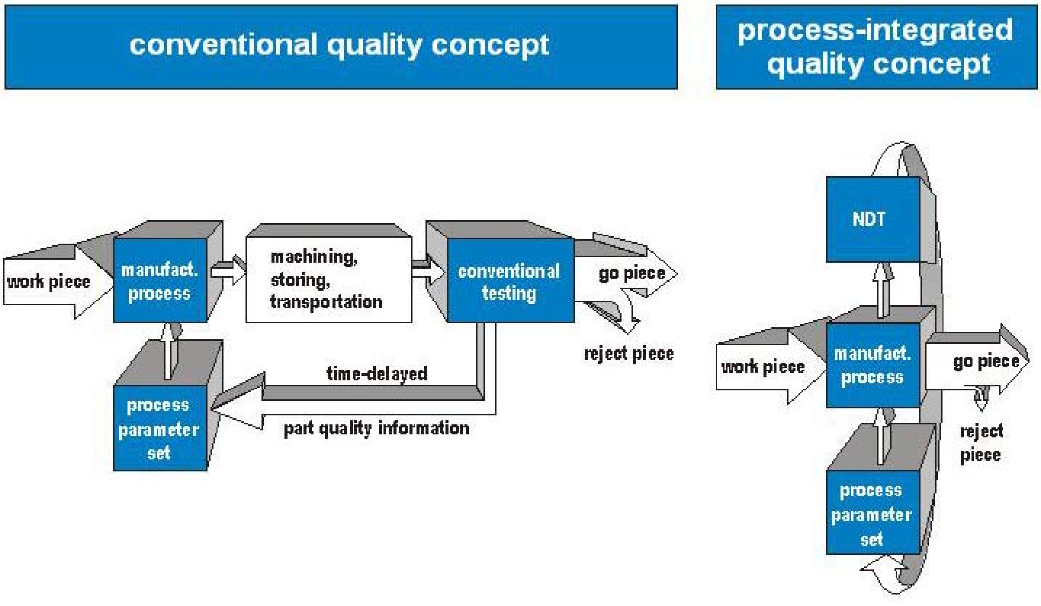

Figure 1: Quality assurance – conventional ws. process-integrated

Basics of eddy current technique

1.1 Working principle

Electromagnetic measurement techniques use the effect of changings in the electrical conductivity and in the magnetic permeability at local defect areas inside metallic materials. To realize a fast and wide-range defect detection combined with a high lateral and depth resolution, it is necessary to develop a sensor system that is most fitting to the geometry and material to be tested, and to adjust the test parameters with high accuracy.

According to the test task it is therefore to be examined whether a clear correlation between the mechanical and physical characteristics of the material exists [1, 2]. Eddy current measuring systems work by generating a high frequency alternating current flowing through the windings of an excitation coil, which interacts with electrically conductive materials near the coil (figure 2). This high-frequent current generates an alternating primary magnetic field, which induces an eddy current distribution inside the electrically conductive test material. Like conventional alternating current effects, a secondary magnetic field is generated by the eddy currents, which shows opposite direction and a variable phase shift towards the primary field. Overlaid to the primary field, the resulting field induces an alternating voltage inside a second coil called measuring coil, which is provided with a large number of windings to generate a high signal amplification at a good signal-to-noise ratio. The recorded operating point of a complex material test signal can be displayed in a graphic complex plane, as it contains real and imaginary signal parts. The position of the operating point is a characteristic value for a concrete geometry and material combination.

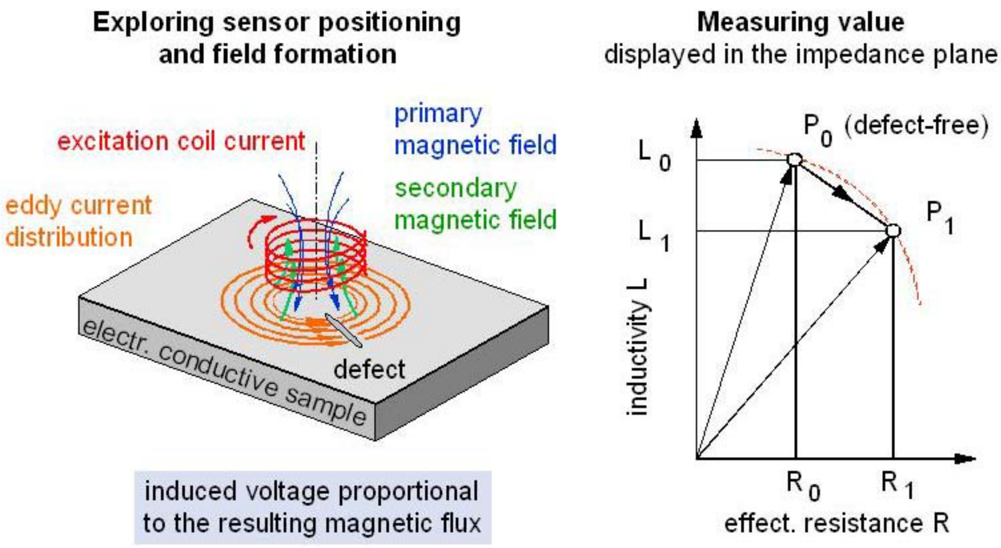

Figure 2: Eddy current technique – working principle

To increase the measuring accuracy and to eliminate the influence of disturbing effects, such as lift-off and tilt effects, it is useful to vary the test parameters such as test frequency, signal amplitude or phase shift. These steps allow an exact adaption of the system in order to detect both surface-near and inner defects inside even thick-walled pieces.

1.2 Remote field eddy current technique

Conventional applications of the eddy current technique use either air-core coils or ferritic core coils, which are mostly realized as exploring coils. This test method is restricted concerning the frequency-dependent maximum penetration depth. It only reaches defects near or with contact to the sensor-sided sample surface and therefore puts strong limits to the location of detectable defects within the test sample. A simulation of the field characteristic reveals the fundamental status (figure 3, top). The eddy current distribution within the test sample under the sensor and the magnetic field lines enclose the excitation coil. Caused by the electrical conductivity of the sample material, they are slightly deformed out of symmetry. Inside the sample's material the field is focussed not very strongly but spreading outwards. The extension of the remote field does not reach the sensor-sided sample surface and is not very distinct. This means it cannot be used for defect detection beyond the sensor-sided surface. A higher local resolution at the use of higher test frequencies is followed by an additionally reduced penetration depth.

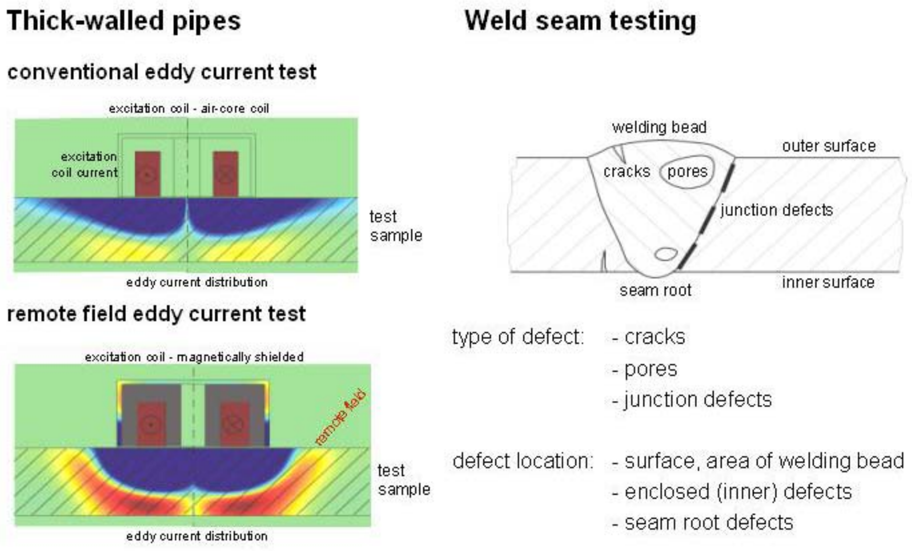

Figure 3: Eddy current techniques – exemplary applications

A suitable technology to detect enclosed defects and defects at the sensor-opposited sample's surface, such as material separations, cracks, pores or junction deficits inside of electrically conductive materials, is given with the remote field eddy current test method. This technique has been proved in detail during the last years and lead to a new horizon of nondestructive testing. A magnetic shield, realized by ferritic material with a high magnetic permeability and a very low electrical conductivity, bundles the magnetic field beyond the excitation coil and increases the penetration depth of the eddy current distribution, so that a stronger remote field is created and is able to reach the sensor-sided surface of the sample offside the excitation coil (figure 3, bottom).

Suitable sensors for the detection of hidden and enclosed defects are realized as shielded sensor coils containing a spatial separation of excitation and measuring coil system. A magnetic shield without electric conductivity bundles the magnetic field and focusses it towards the test sample's material. Within the material there's only few influence of the primary field, so that a detection of hidden defects inside the material is possible with high sensitivity and local resolution.

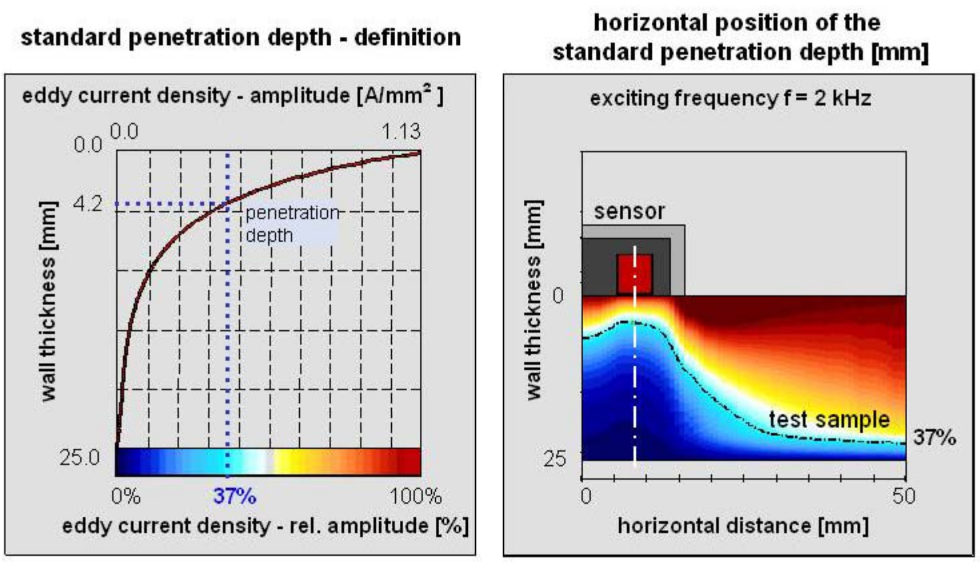

Figure 4: Standard penetration depth analyzes simulation results

1.3 Simulation-supported sensor development

Former research work has dealt with a static 2D simulation of the field formation inside rotary symmetric sensor-material-arrangements (figure 4). The results lead to a basic understanding of the magnetic field in dependence on exciting frequency, electrical conductivity and magnetic permeability of the tested material or the lateral distance of measuring and excitation coil (figure 5). It was found that a defined phase matching of the

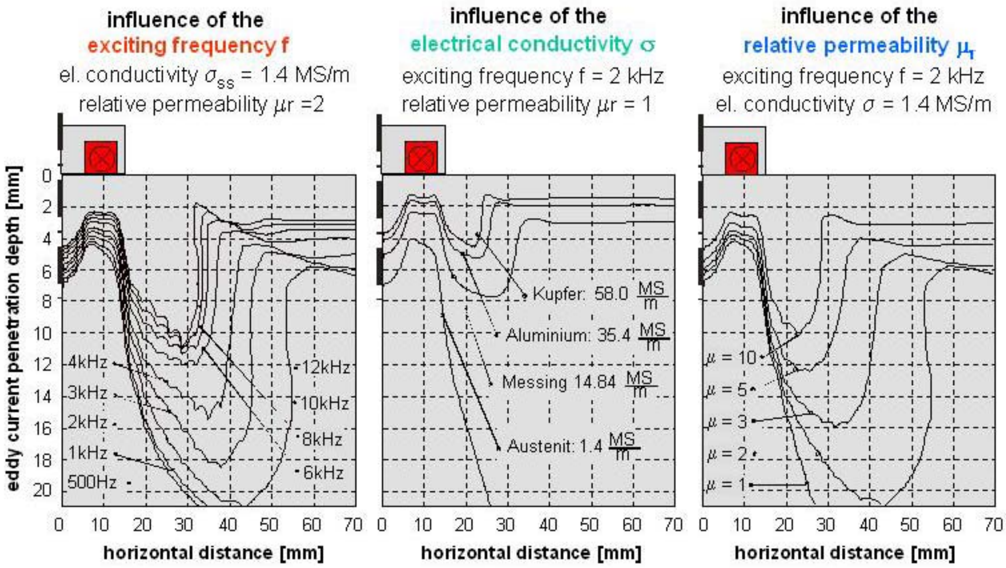

Figure 5: Penetration depth as function of test parameter variation

measuring signal helps to separate disturbing effects like lift-off or tilting effect from the defect information of the measuring signal. Turning the disturbing signal effects completely into one of the signal parts, e. g. along the real part axis, minimizes their effect on the defect signal information and can mostly be eliminated from the signal (figure 6).

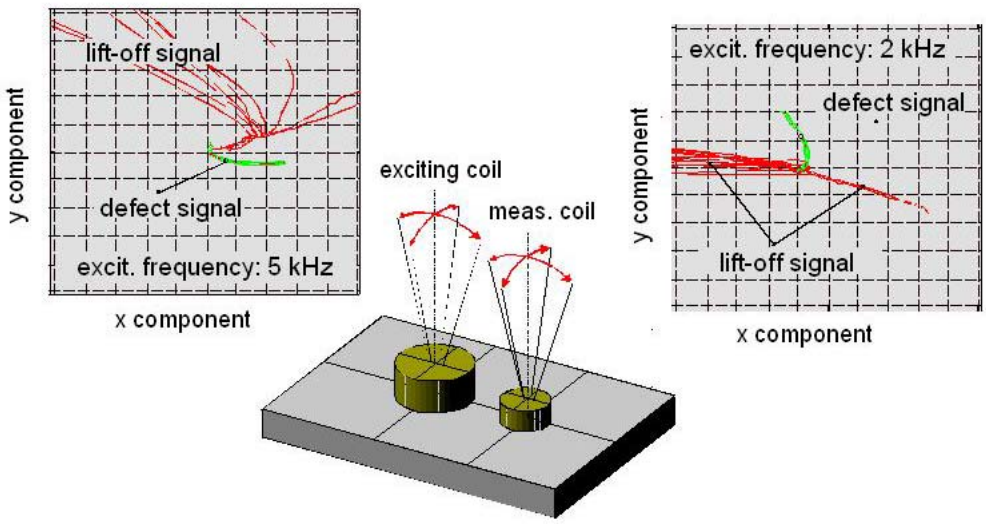

Figure 6: Separation of defect signals and disturbing signals by phase selection

Recent research work has created a 3D model of an applied and shielded remote field sensor to an electrically conductive metal sheet with a 75% depth defect on the sensor-opposited surface of an aluminium plate (figure 7). Using the finite element method and

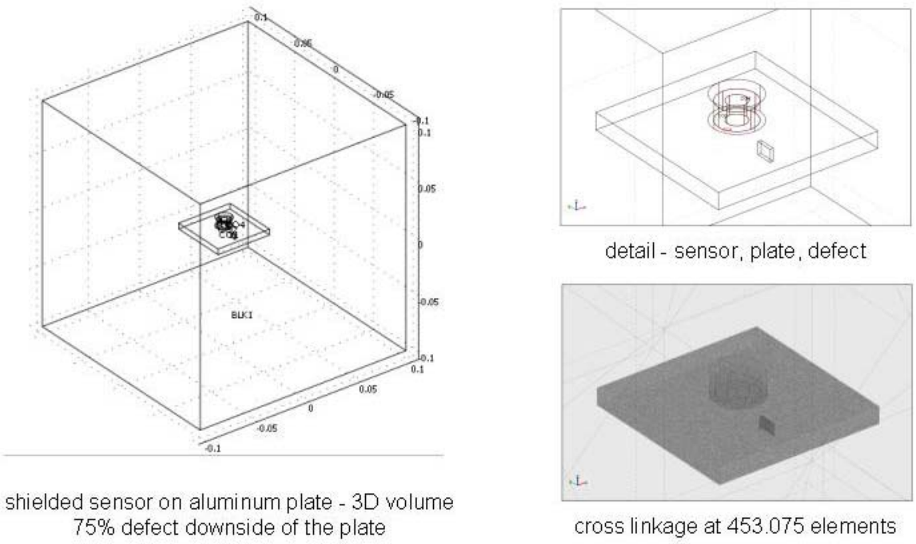

Figure 7: 3D model – simulation of eddy currents and magnetic fields

supplying the model with about 450.000 elements, the results show the dynamic evolution of the eddy current distribution under the sensor (figure 8) and the magnetic potential distribution over a half phase cycle of 180°, the latter displayed as real (x) and imaginary (y) part. The eddy current distribution shows by hand of the x component an eddy current distribution with a growing near/remote field border moving phase-dependent away from the sensor to the bottom of the aluminium plate, with a beginning visibility at about 30° phase. After a half period this circle begins again with changed signs. The defect represents a local disturbance that leads to a locally higher eddy current density.

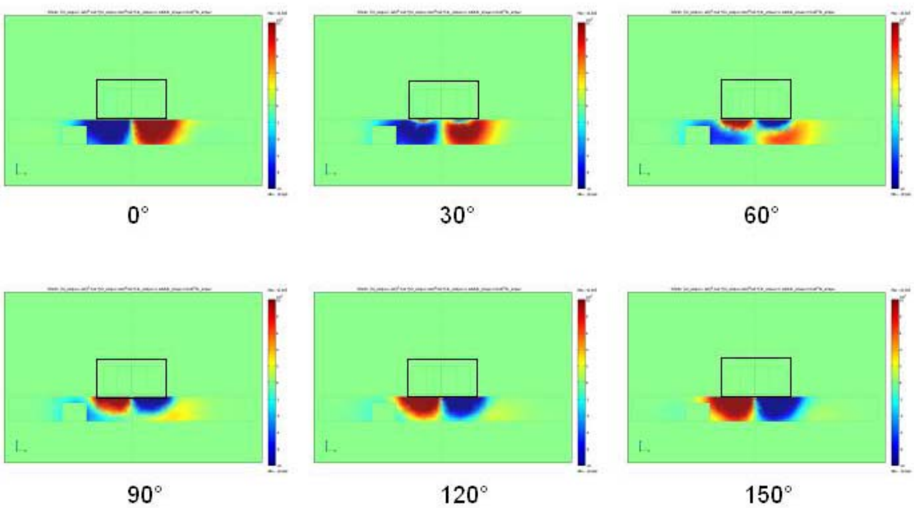

Figure 8: Simulation – eddy current distribution (x component)

The magnetic potential distribution is shown by hand of the x and y potential component, which can be measured with a measuring coil and which are both layed into the drawing plane in horizontal resp. vertical direction (figures 9, 10). Discussing a half period of the measuring signal emphasizes the disturbing influence of the hidden defect on the potential distribution at the top surface of the material, especially at phase signal angles of 30° and 120°. Again, after 180° phase shift the process starts with changed sign. This is a plastic display of an eddy current distribution under displacement influence of a present defect inside a test sample, which is also measurable in practice.

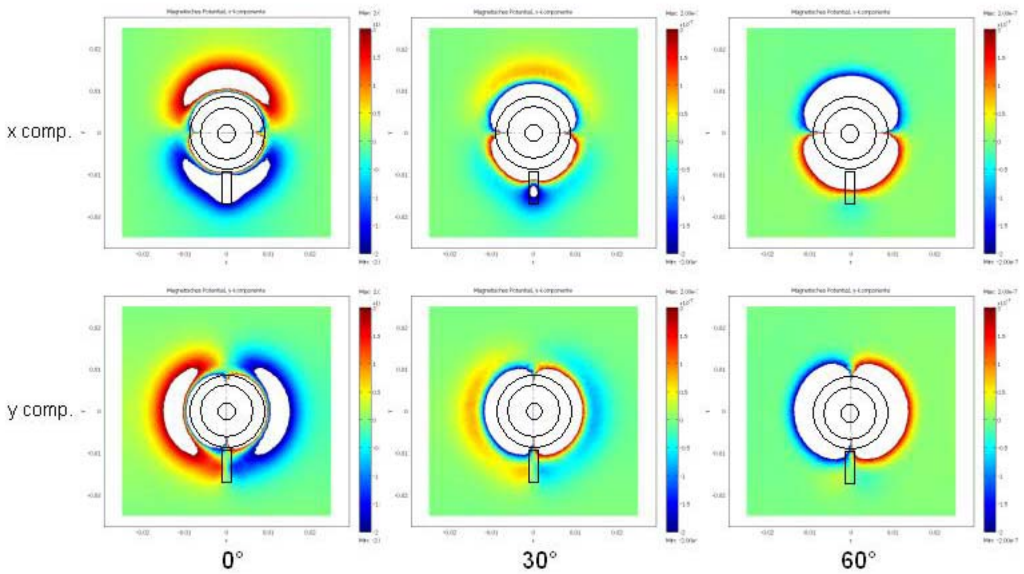

Figure 9: Simulation – magnetic potential I

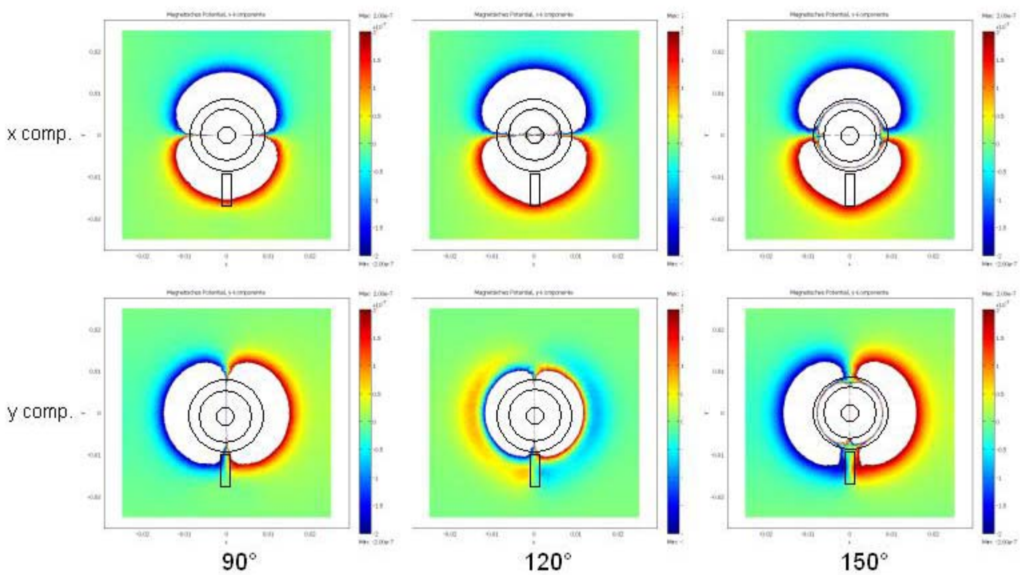

Figure 10: Simulation – magnetic potential II

Applications

2.1 Thick-walled austenitic pipes

Concerning the cases of damage inside of thick-walled austenitic components, e.g. pipes, it is necessary to be able to inspect the whole cross section of the wall. Therefore an inspection technique with sufficient sensitivity to detect defect location and defect depths as well as expansion of defects inside the base material must be applied. A suitable technique for this application is the eddy current remote field technique. Former research work dealt with the 2D simulation of eddy current distributions in order to create an optimized sensor design, concerning an entire inspection of austenitic materials with a wall thickness up to 25 mm. Recent development and adaption work concerning the remote field eddy current technique have dealt with an optimization of the defect detection in order to find 10%-defects at the sensor-opposited, i. e. the inner surface of the pipe. Therefore, some austenitic test pipe samples were equipped with inner surface defects in form of saw notches and spark erosion notches, which were positioned in longitudinal and circumferential direction of the pipe. Additional test defects were placed under 45° to the longitudinal pipe axis. The defect depth was set within a range of 10% to 40% of the pipe's wall thickness [3, 4].

With the FEM simulation results it is now possible to scan austenitic pipes with a remote field eddy current sensor mounted onto a remote controlled manipulator in order to scan the complete volume of the pipe material, for example manufactured of austenitic steel X10 CrNiNb 18 9, No. 1.4550. Figure 11 shows a section of a 1.4550 austenitic pipe with outer diameter of 220 mm, a wall thickness of 20 mm, and typical test defects at the inner surface. Eddy current C-scan results of a pipe containing 40% to 10% longitudinal defects are displayed besides. Even the sensor-opposited 10% defect can be identified distinctly.

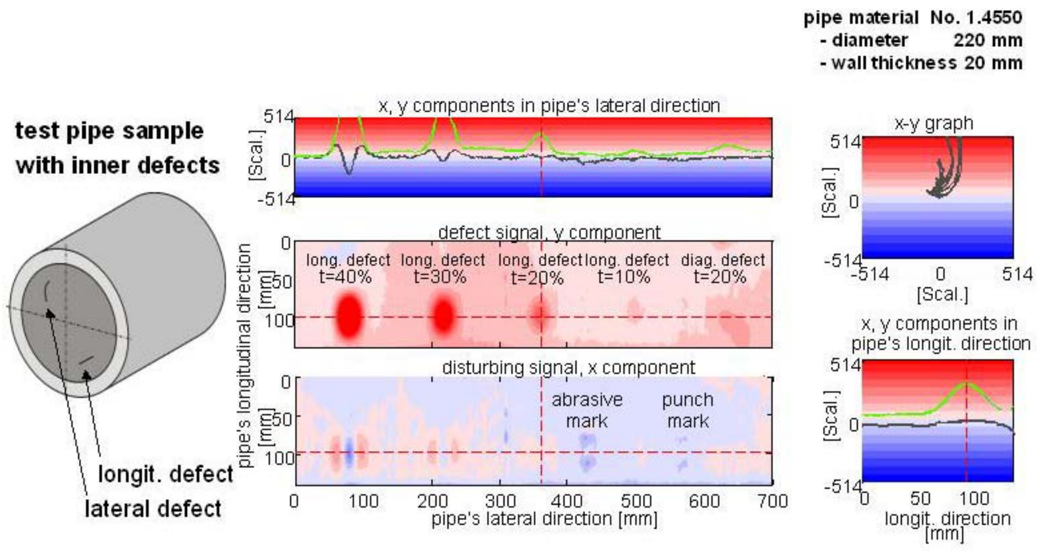

Figure 11: 2D signal analysis of longitudinal inner defects

In order to separate outer and inner surface defects as well as enclosed defects inside the wall volume it is necessary to determine the defect's size and three-dimensional extension by analysis of the signal amplitude and to adjust the phase shift of the eddy current measuring signal in a way that the phase angle is a position indicator for the defect's distance to the surface. An optimum phase adjustment leads to defined decisions concerning position and surface distance of a defect (figure 12).

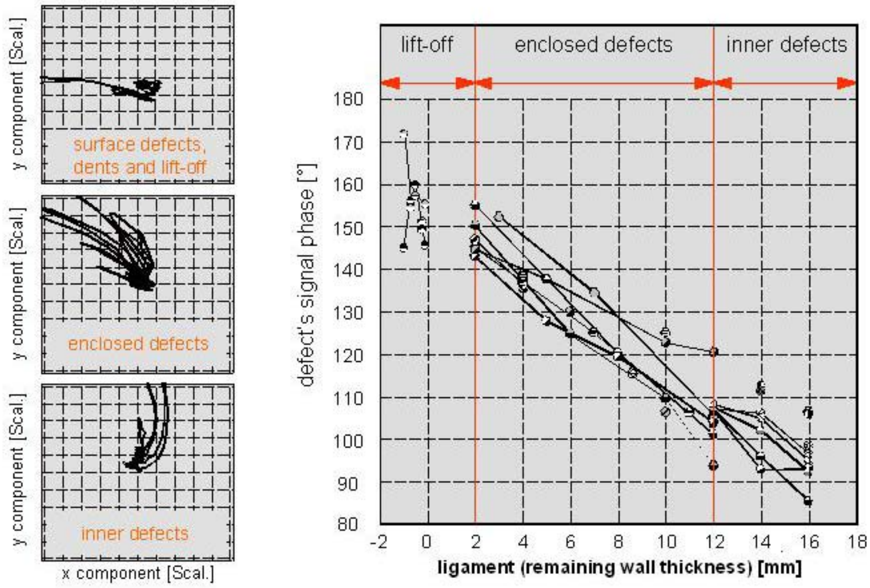

Figure 12: Defect depth position – signal phase and ligament

2.2 Light metal weld joints

2.2.1 Basic research

Crack-like defects, pores and junction defects are kind of typical category at welding light metal products. Rising demand on quality and reliability of semifinished products and parts therefore create a present need to realize sensitive, nondestructive techniques, which are able to detect and to characterize crack-like and volume defects, positioned surface-near or within the wall volume, inline after the welding process.

Numeric calculations have the potential to support the analysis of physical processes inside the aluminium weld seam, according to their interaction with electromagnetic remote fields and eddy current distributions. Former research works show FEM based numeric calculations of magnetic field distributions inside of aluminium pipes, which were examined to get information concerning crack-like defects inside the material [5, 6, 7, 8]. The scientific publications of [9, 10, 11] dealt with the possibility of getting new information about eddy current and magnetic potential distributions by use of simulation work in order to optimize sensor techniques and test parameters.

Another thesis was formulated by [12] as they simulated and analyzed electromagnetic field distributions in coaxially welded heat exchanger pipes in order to prove the sensitivity of the remote eddy current technique in comparison to the established ultrasonic technique. Systematic works on the field of eddy current technique development are fist discussed by hand of defect testing of thick-walled aluminium plates in the 1998 [13]. It pointed out the fundamental ability of the remote field technique to analyze thick-walled, non-ferrous plates.

Recent scientific works at the Institute for Materials Science at the University of Hannover, Germany, dealt with the qualification of the remote field eddy current technique in order to detect and to classify defects inside thick-walled, non-ferrous materials, such as austenitic steel or aluminium [14, 15, 16]. These results proved the unexhausted potential concerning a successful testing of light metal weldings.

An important criterium for the practicability of a testing technique is the reliable detection of all kinds of relevant defects inside a test sample, such as inner and outer defects or enclosed ones fully hidden inside the wall material. Effective parameters to reach this aim are the geometry of the sensor, the exciting current and the test frequency as well as the optimization of the phase shift of the measuring signal. With an exact adjustment of these parameters it is reliably possible not only to detect the different kinds of the mentioned defects but to distinguish between them, based on the actual measuring result (figure 12).

Serial investigation of straight bead welded light metal pipes demand on a measuring equipment that guarantees a defined sensor position upon the test sample's surface. Therefore, a special sensor carriage was constructed and realized to guide the sensor in a constant distance towards the sample's surface even at different sample diameters (figure 13). Several types of aluminium pipes containing different types of typical defects were tested using this hardware.

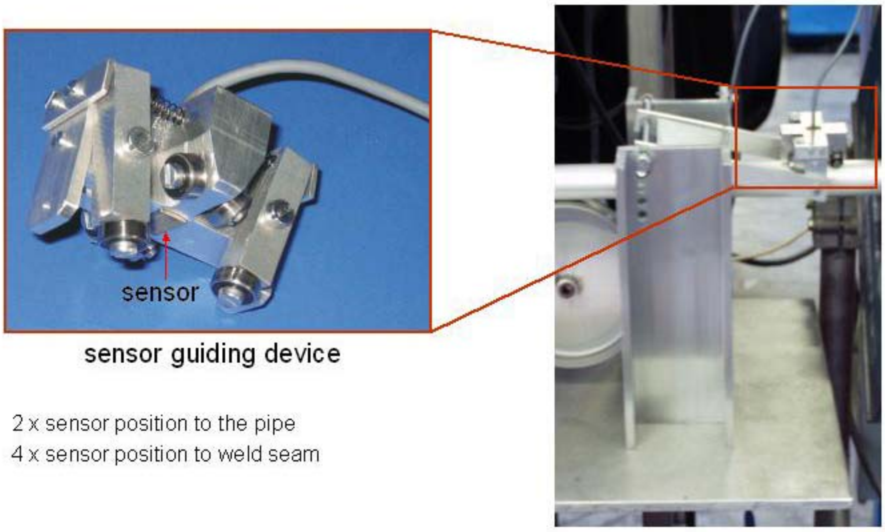

Figure 13: Process-integrated remote field eddy current testing

2.2.2 Results

At figure 14 the measuring result for a defect-free 32x0.8 mm aluminium pipe welding is shown. The background noise is at low level and without relevant local deviations from the mean value.

Typical aluminium band damages that can cause local defects within the course of the weld seam are humid or waved band edges and dents at the edges, which are caused by former working steps, such as edge mismatch or a varying gap width. These influences lead to typical weld damage aspects.

Present humidity at the band edges is heatened by the welding system and vaporizes. The vapor displaces the inert gas during welding and leads to oxides in the seam. A remote field eddy current line-scan of the seam reveals discontinuous signal behaviour at the defect position, as the system shows different signal forms dependent on the type and formation of the defect. Caused by waved or denty band edges, the remote field eddy current line-scan reveals a different defect behaviour, dependent on whether the defect covers the whole wall cross section or is just a hidden defect at the inner surface of the wall. Typical for waved edges is the presence of periodical defect signal components. Dents at

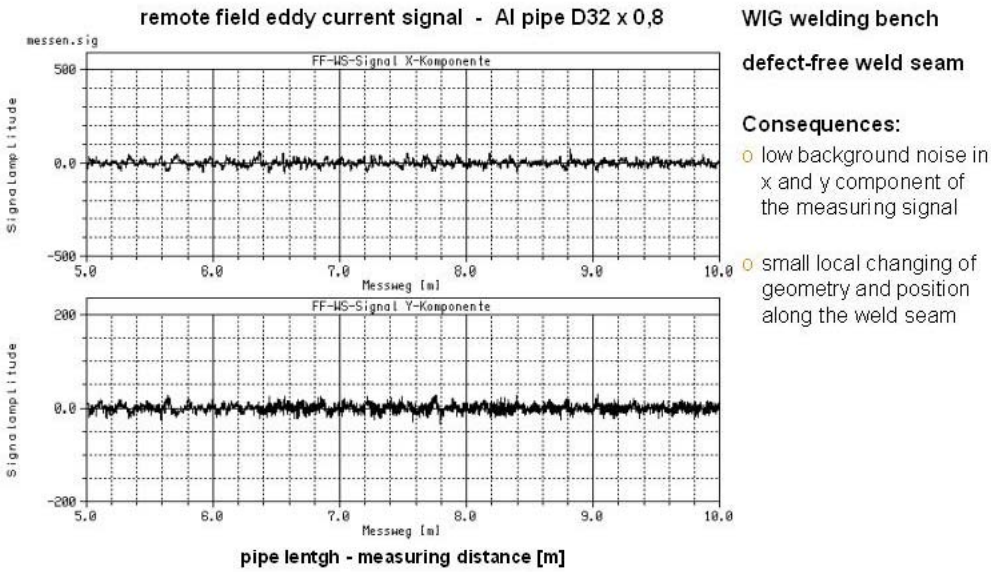

Figure 14: Measuring signal of a defect-free weld seam

the edges cause a defect formation similar to the vapor-caused defects. These discontinuous signal elements show also a different formation of direction and amplitude, dependent on being caused by full wall thickness defects or hidden defects.

External and inoperable disturbing effects are e. g. caused by external electrical and magnetic fields, like beside cables or thyristors. These effects do not show a significant increase of the noise level or disturbing peaks within the measuring signal, which can be proved by recording a reference signal without a test sample. System-based defects are often caused by varying the welding parameters, e. g. the distance between welding electrode and pipe surface. Therefore, the weld seam shows local widenings and deepenings of the molten bath and zones of worse fusion between seam and basic material. The measuring signal reveals these zones by showing certain signal peaks. A typical aspect

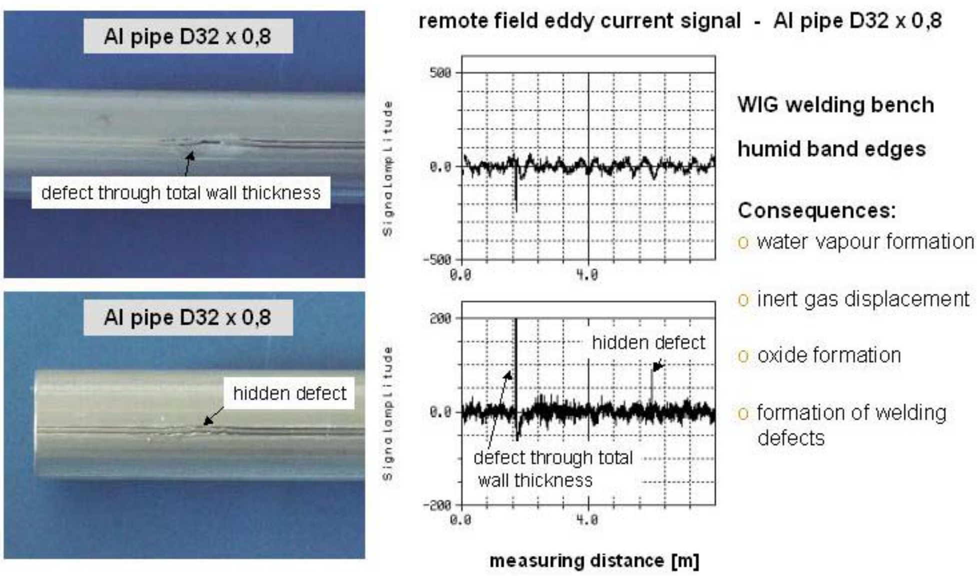

Figure 15: Exemplary view and measuring signal of a defect weld seam caused by humid band edges

of a damaged weld seam is shown in figure 15 together with a corresponding measuring signal, which distinguishes clearly between defect-free areas, hiddn defects and defects over the full wall thickness.

Summary

Recent research work at the Institute for Materials Science at the University of Hannover, Germany, has qualified the remote field eddy current technique for a sensitive and fast detection and classification of hidden defects inside thick-walled, non-ferrous materials, such as austenitic steel or aluminium.

At thick-walled austenitic steel pipes it was reliably possible to detect hidden 10%-depth-defects within a wall thickness of more than 20 mm and to typify them concerning their thickness, their direction and their distance inside the wall from the wall's surface.

Aluminium pipes with weld seams could be tested successfully in order to find and to characterize hidden defects in order to optimize the welding process. Different defect types caused by process-dependent and external sources can be easily distinguished and identified using the remote field technology.

The displayed results point out the unexhausted potential concerning a successful defect testing of thick-walled, non-ferrous metal components as well as of light metal weldings.

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