Mechanized Crack Detection on Austenitic Weld Seams with Eddy Current Technology

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Abstract: Since no weld is entirely perfect crack detection on austenitic weld seams is an important task for which NDT is usually applied. Due to the fact that austenitic weld seams generally contain δ-ferrite which is ferromagnetic eddy current technology is often considered to be inapplicable. In this paper it is shown that eddy current crack inspection is a reliable means to this regard despite the inconvenience of δ-ferrite being present. Its application can be implemented either manually or fully mechanized. The application by means of crawler devices for the inspection of pipes is performed on a regular basis.

1. Introduction

Since no weld is entirely perfect and despite all efforts being taken while designing, producing and inspecting welded components discontinuities occur especially in the areas of the weld and heat affected zones [1]. Prior to selecting a NDT-technology for a specific inspection it is of utmost importance to gather information about the location and type of defects, e.g. cause for the defect, probable size and orientation, therein taking into consideration crystal structure, production steps, material properties, environmental conditions, and so on. In the case of austenitic weld seams defects are mostly due to cracks, residual stresses, and variations in the crystalline structure and thus the material properties; they are denoted as defects if they cause a failure of the component [2]. As cracks are often considered more harmful than other defect types crack detection on weld seams is a necessity which can be successfully met by means of applying eddy current technology [3].

2. Austenitic steels

On cooling carbon steels transforms austenite to a mixture of ferrite and cementite. Changing the alloy to larger amounts of chrome and nickel suppresses this transformation during the cooling process thus allowing the material to slowly transform fully to austenitic material after solidifying to δ-ferrite at first [2]. However, in case of too rapid cooling it is possible that δ-ferrites remain in the material; the formation of δ-ferrites can still be reversed by proper heat treatment. Yet, austenitic material without δ-ferrite is less easily formed at higher temperatures.

Austenitic steels are covered by a very thin, yet stable oxide film which is rich in chrome and reforms quickly if damaged thus rendering the steel stainless. This film will form out to be very thick if the material is not properly protected from the atmosphere during welding or heavy grinding. In such cases there is a chrome depleted layer below this layer and both layers have to be removed in order to regain the stainlessness.

Sensitisation is another danger occurring when austenitic steel is heated in the range from 500°C to 800°C. By this heating which occurs for example during welding the risk is high that the chrome will react with the alloy's carbon forming chrome carbides. Thereby the availability of chrome is reduced and provision of the passive film is reduced leading to preferential corrosion. Therefore a very well controlled heat input is advised along with the addition of small quantities of titanium or niobium which will avoid the undesirable formation of chrome carbides [2].

3. Causes of weld imperfections and cracks

Despite the fact that many improvements have taken place in welding technology, occasional failures of weld joints still take place and reinforce the need for the testing of weld seams and adjoining areas. A major cause for the difficulty in manufacturing reliable weld seams is the fact that the heat affected areas cool rapidly after performing the weld process. This results in thermal stresses which may lead to cracking as well as entrapment of gases or foreign materials within the weld area. Such discontinuities interrupt the typical microstructure of a weld weakening mechanical, metallurgical or physical characteristics of the base material or the weld. If a discontinuity renders the welded area and thereby the component unable to meet the specified minimum demands it will be considered a defect. Weld defects include cracks, cavities, spatter, incomplete achievement of penetration, fusion or shape [6].

Cold cracking is a transgranular defect which occurs well below the solidification point of the base metal and occurs if some essential conditions are present; one of these is the presence of diffusible hydrogen in the weld seam [6]. Since this effect is of no importance for austenitic steels, preheating is seldom required [5].

Stress corrosion cracking is a large risk whenever using austenitic steel since deep cracks can be formed in the material due to the presence of chlorides in the process when the material is exposed to tensile stresses, e.g. residual stresses or thermal stresses induced by welding processes. Significant increases in nickel help to reduce this risk [2].

Since cracks, being more or less linear fissures, tend to grow under stress they are often considered as the most dangerous defects. They can be differentiated by location and orientation as well as temperature of formation. For example, hot cracks occur during solidification or the cooling process and are caused by the presence of low melting impurities in the base metal. In the case of austenitic steels these elements include among others boron, sulphur, phosphorous, arsenic, and tin. Since these impurities remain liquid long even after the base material is solidified they settle at the grain boundaries. Being brittle they act as focus points of thermal stresses leading to cracks and it becomes obvious that this effect increases with the grain size [6].

4. Aspects of welding austenitic base materials

This tendency of austenitic material towards heat-induced cracking is met by applying weld deposits containing a low percentage (4 to 10%) of δ-ferrite [5]. This partially ferritic solidification process allows for a higher dissolving power regarding impurities such as phosphor, niobium, boron, and sulphur thereby in turn reducing the tendency towards heat-induced cracking [2]. Furthermore δ-ferrite impedes the recrystallisation process thus encouraging the forming of finer grains. Thereby the grain boundaries' surface is significantly enlarged, and in turn the danger of low melting impurities taking up on large areas of the grain boundaries is reduced. Additionally ferrites offer a lower thermal expansiveness [2].

The welding behaviour of austenitic steel differs from ferritic steel. Notably the almost doubled thermal expansion (compared to unalloyed ferritic steel), the high inclination to oxidation due to the high chromium content as well as the sensitivity to heat-induced cracking have to be taken into account when welding austenitic material [4].

The increased thermal expansion combined with the lower thermal conductivity has to be handled by means of additional cooling systems to reduce warping and residual tensions. Additionally, the weld seam area and the heat affected zone have to be protected from air resp. oxygen to cope with the high inclination to oxidation. This is mostly done by applying an appropriate gas-shielded welding technique with special care [7].

5. Some NDT-technologies for crack detection on austenitic weld seams

Several references [6], [7] provide detailed reviews on basic NDT-methods which can be readily reviewed. These range from visual, radiographic, and ultrasonic examination over magnetic and eddy current techniques to acoustical emission methods. Depending on the case of operation each method offers certain advantages and disadvantages.

Radiographic methods especially excel in inspecting materials of all sorts and detecting flaws over the entire thickness even far below the surface, yet they suffer from their lack of mobility, the often time consuming process to visualize the results, and the necessity to shield the surroundings from the harsh radiation. Ultrasonic methods also allow for inspection of all sorts of materials, they offer a high penetration capability and a quick response time. However, they mostly depend on the meticulous application of coupling media. Furthermore small or thin welds may be difficult to inspect, especially if situated near the surface [6].

However, in cases of mobile and fast operation, of not-existing possibility for proper shielding, of having to provide instantaneous results yet lasting data, and/or of not allowing the application of couplants eddy current technology has proven its worth and reliability many times.

Aside from the classic eddy current method it is possible to perform the inspection by applying remote field (eddy current) technology which has the advantages of high plane and volumetric resolutions. Thereby it is possible to inspect even thick-walled pipes over their entire wall thickness [9]. However, remote field appliances tend to be of larger-scaled design (roughly up to factors of 4:1 compared to standard eddy current devices). These facts are aggravated by the notably low inspection velocity (approximately 0.5 m/min) when inspecting machine-weldings.

However, standard eddy current appliances used for the crack inspection of austenitic base material offer inspection velocities of up to 200 mm/s = 12 m/min thus offering a substantial economic advantage. Naturally standard eddy current inspection will not render an inspection over the entire wall thickness due to the skin effect but rather data of the surface and depending on the eddy current system and its adjustment also of sub-surface areas on the sensor side of the wall. Best results are obviously obtained on cracks which are open towards the surface; however, this openness to the surface has not necessarily to be the case.

There are references to other eddy current technologies attempting to detect cracks on austenitic base material with special probe technologies [10]. However, the results show just the experimental stage as well as results on austenitic base material only.

6. A short reminder of surface crack inspection by means of eddy current systems

If a voltage is applied to a coil a current is driven through the coil and causes a primary magnetic field which is situated within the coil's space as well as in its vicinity. This magnetic field induces eddy currents within a nearby electrically conductive test object. These eddy currents in turn cause a secondary magnetic field which is opposed to the primary field thus changing the coil impedance of a measuring coil (fig. 1).

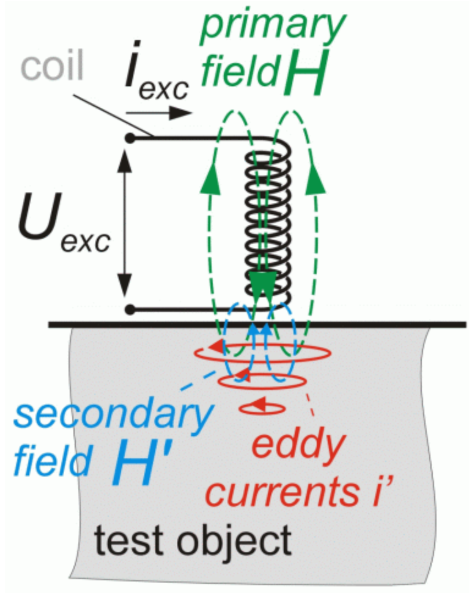

Fig. 1: Eddy current inspection system

The connection of two coils connected in bridge circuit results in the established difference system. Depending on which coil experiences a change in its impedance, i.e. which magnetic field is disturbed by a defect such as an open crack, the measuring signal within the impedance plane is changed in phase shift and amplitude.

If the obtained data points are coloured from green to red depending on the increasing weighting of the defect, a localised coding along singular tracks is achieved. Combination of several tracks over the surface of a test object delivers an easily interpreted representation of the defect situation on the test object's surface (C-scan).

Having established the availability to unambiguously depict three-dimensional data (defect severity over length and width of the test object) in two dimensions the task to obtain the measuring data remains. In case of single or welded flat plates this is accomplished manually or by means of automated scanning devices (fig. 2).

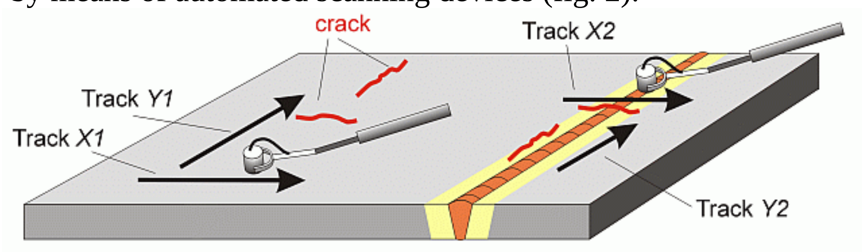

Fig. 2: Two-dimensional scanning of test object (left standard sheet, right welded sheets)

The positioning of the sensor gets more difficult if the test object consists of non-flat objects, e.g. pipes. However, it is still possible to transform the three-dimensional C-scan which can be projected on the inspection area to a two-dimensional depiction.

7. The challenge for eddy current technologies: welded austenitic material

Welding of two or more parts of the preferably same metallic material mostly by means of adding resp. filling in welding material involves a certain amount of heat being fed into the areas to be joined. In our case (fig. 3) the weld joint is a butt joint consisting of two pipe sections.

Figure 3 shows a calibration body of Ø408 mm and a wall thickness of 14.8 mm. A circumferential weld seam joins two pipe parts at 102 mm. Seven artificial notches were manufactured by means of electrical discharge machining resulting in a uniform notch-width of 0.25 mm. The depths of the notches amount to 1.5 mm and 3.0 mm resp. 10% and 20% of the wall-thickness. Moreover, notches 1 to 6 are oriented circumferential, whereas notch 7 has a longitudinal orientation. It has to be noted that the surface was grinded in the area of the weld seam as well as the heat affected zone and that the width of the notches is uniformly 0.25 mm.

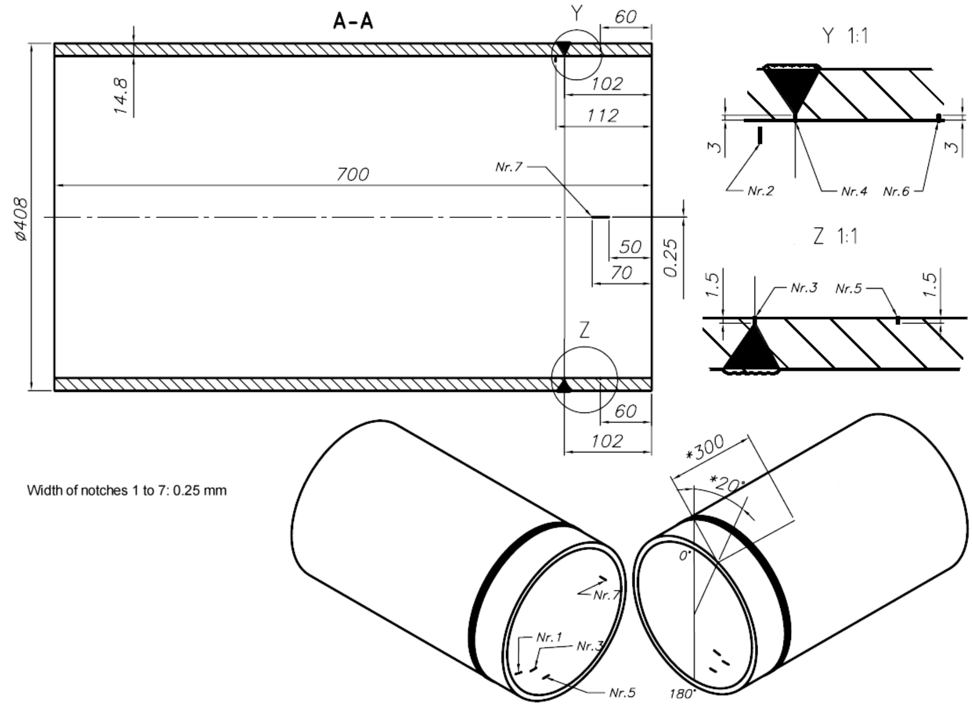

Fig. 3: Austenitic calibration body featuring a circumferential weld seam and seven calibration notches

As in paragraph 4 explained welding of austenitic base material mostly implies δ-ferritic weld material. Actually the weld material is heated into its soluble state during the welding process and due to the very rapid cooling δ-ferritic structures which are normally only of temporary nature are caught in their crystalline structure before they can transform into austenitic material [2].

Furthermore, it has to be noted that the presence of δ-ferrite implies that the concerned parts show a ferromagnetic behaviour [4] which varies with the percentage and distribution of ferritic particles. Thus the primordially paramagnetic behaviour of the austenitic base material is still present, but within the weld seam areas the magnetic behaviour changes to ferromagnetism. The hysteretic behaviour of the ferromagnetic weld seam areas therefore does not easily allow for standard eddy current crack detection on austenitic base material because the (δ-)ferritic areas normally render only massively distorted eddy current signals.

8. Improved eddy current probes for crack detection on austenitic weld seams

In order to minimize and control the effects of the δ-ferritic or rather ferromagnetic parts of the test object's material the eddy current probe systems underwent major examinations leading to the development of a new eddy current probe system. The new probe allows for the detection of defects on the side of the test object which is turned towards the probe. The measures which had to be taken to eliminate the disturbing signals of the ferritic material parts claim their tribute in so far that the penetration depth is reduced. Therefore the new eddy current probe systems were designed for detecting defects near the surface, however, it has not necessarily to be the case that the defects are open to the surface. Additionally, the probe systems were optimized for detection of crack-like defects.

The detection of cracks is almost independent of their orientation, i.e. the new eddy current probe system allows for the detection of all cracks near to or at the surface. However, a second orthogonal inspection track will be necessary to enable the inspection system to properly resolve the orientation information within the C-scan. This is due to the fact that the evaluated amplitudes of orthogonal defects suffer from significant phase shift.

It has to be noted that a technical necessity is to have the inspected areas to be notch-free grinded beforehand in order to obtain inspection results of the highest quality. This also applies to the heat affected zone.

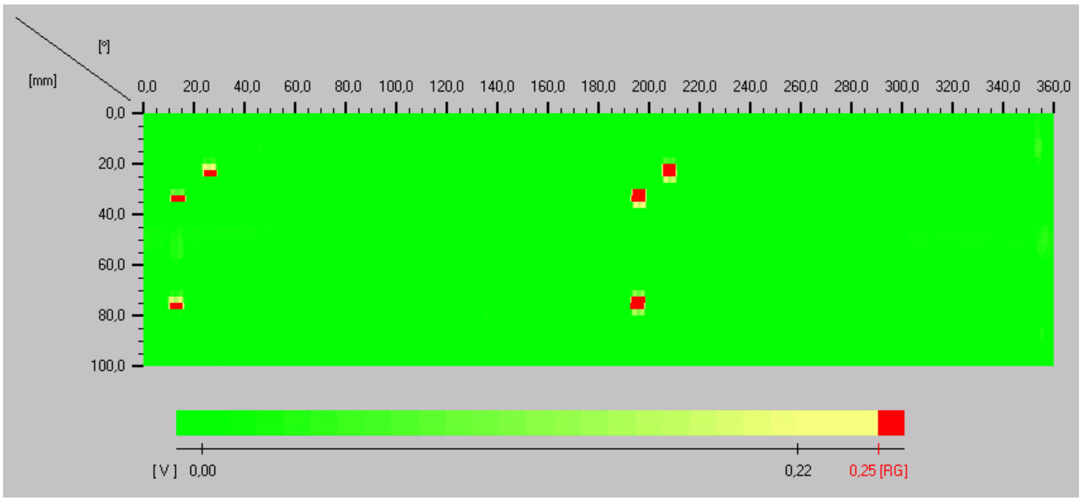

Fig. 4: Exemplary C-scan of the calibration body

At the bottom of figure 4 a colour chart explains the relation between obtained voltage data from the new eddy current probe system and shown colour. Above the colour chart an exemplary C-scan is depicted relating to the calibration body which is described in paragraph 7 and shown in figure 3. It is obvious that only the circumferential notches 1 to 6 (fig. 3) are demarcated whereas the longitudinal notch 7 is not visible in the C-scan due to the phase shift of the orthogonal defect which lowers the amplitude below the registration level RG (fig. 4 and 5). This is due to the fact that the sensor was optimized in that regard that the anticipated defects which occur in longitudinal direction of the weld seam are safely detected. Of course, an optimization in favour of defect detection orthogonally to the weld seam is possible.

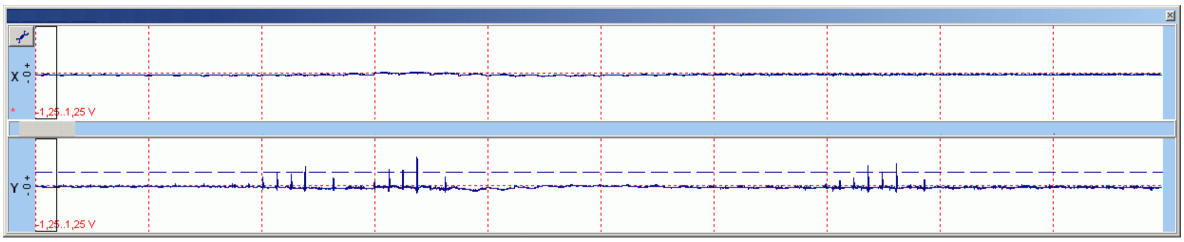

Fig. 5: Exemplary time-domain data corresponding to the C-scan shown above

It is easily seen that not only notches 5 and 6 outside the weld area are shown properly but also notches 1, 3, and 4 right under the root of the weld seam as well as notch no. 2 scantly beside the weld seam are clearly indicated. This evinces neatly that the new eddy current probe system is able to simultaneously detect cracks in austenitic base material as well as in (δ-)ferritic weld seam material.

9. Practical application

The described detection of cracks in austenitic base and weld material can be performed manually or by means of partly or fully mechanized devices. The latter will be applied when a precise and detailed scan of an area is needed or the area to be inspected is not accessible, e.g. deep within a pipe. On flat surfaces newly developed A4- and A3-sized scanning devices can be applied for exact and fast scans of areas. Moreover, the inspection of pipes is performed on a regular basis with so called crawler-systems [3].

Crawlers are mechanical devices which can be either flushed through a closed pipe or which move through a pipe by its own propulsion. If mechanical crawlers with power supply by umbilical cords are used the operating range is limited to approximately 50 m primarily by the weight of the trailing umbilical cord. The crawlers are able to climb vertical stretches, negotiate branch-offs, and move around sharp bends. Nevertheless it is easily possible to position the crawler itself as well as the attached tools (fig. 6).

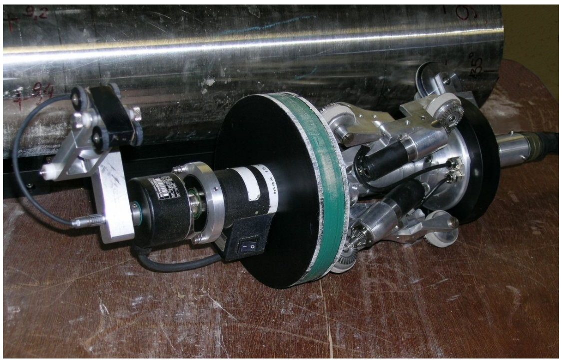

Fig. 6: Crawler with eddy current probes

The probe positioning system has to fulfil high demands in particular since it has to make sure that the probe is always kept in a proper distance to the inspected surface despite oval surfaces of the test object (fig. 7). Another aspect is the safe removal from the inspection i.e. danger zone in case of a failure of the power supply. Furthermore the reproducibility of the inspection is enhanced by attaching the crawler's positioning system to the eddy current data.

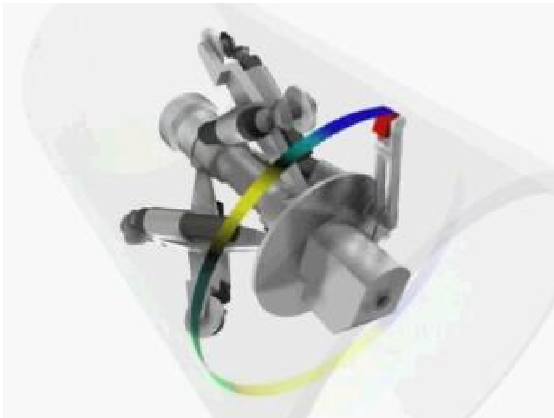

Fig. 7: Principle of crawler probe guiding system

The probe systems are optimized in the regard that they are able to detect defects from 1 mm depth regardless of their orientation. Moreover a clear distinction between surface effects and material separation is made sure.

Aside from the certified application of eddy current technology the presented crawler devices can carry PT-tools, videoscopy systems, suction and blower tools as well as grinding tools. The latter is an ideal complement to the eddy current system in order to provide properly grinded inspection surfaces. Due to a universal adapting system it is possible to attach the same tools to differently sized crawlers which may vary in frame size from DN 80 mm to DN 800 mm.

The applicable eddy current probe systems can vary from rotating to integral inspection probes and inspection purposes ranging from crack detection to wall thickness reduction due to erosion or corrosion (fig. 8). These cases of application are well established for austenitic material and obtain reliable data at a satisfactory speed which can be optimized depending on the rotational speed and the probe's effective measuring width. For example, in case of an inspection regarding wall thickness reduction for a given effective measuring width w of 5 mm and a given rotational speed v of 180 rpm an optimized speed would be set to two thirds of the product $w \cdot v$, i.e. 10 $^{mm}/_{s}$. The angular resolution then amounts to 1° at maximum speed [3]. In case of surface crack inspection this resolution will obviously be optimized so that all calibration defects are properly detected.

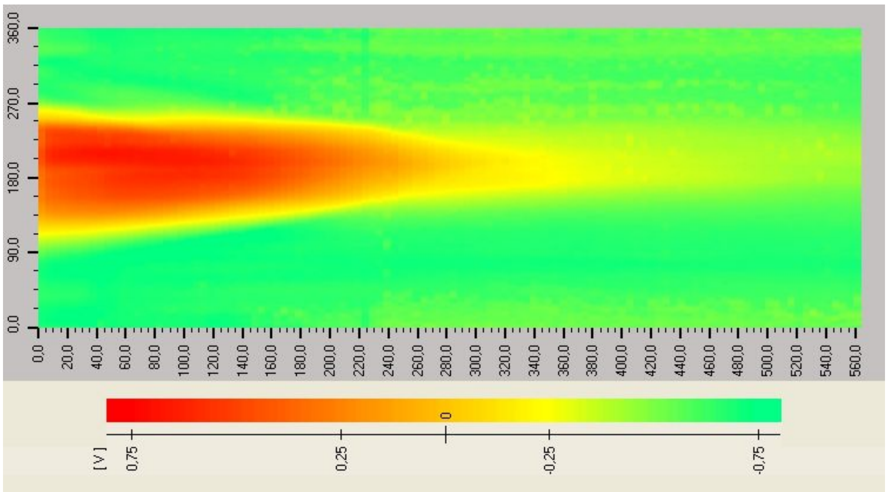

Fig. 8: C-scan of a pipe-inspection regarding wall-thickness reductions

The resulting inspection systems can and have been applied to the inspection of austenitic material regarding wall thickness reduction and crack detection. The new probe system is also applicable to crack detection in the areas of weld seams and the heat affected zones of austenitic weldings. Moreover, it can be applied to ferritic material since the weld areas are more conform to the base material and therefore do not distort the eddy current signal to such an extent as this happened with austenitic material in the past.

Summary

The newly developed probe system allows for the quick manual or mechanized inspection of welded austenitic material despite the presence of δ-ferrite. This probe system can be applied to established crawler devices which are being used for the inspection of pipes. Examples for the detection abilities of the probe systems are given as well as the practical application.

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