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Eddy Current Array Testing of Seam Thin-Walled Tube Made of Steel

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Abstract
This paper addresses testing longitudinal welded joint in a thin-walled tube using semi-automatic eddy current test system and flexible eddy current array probe. The system is by OLYMPUS (EVIDENT). These test results from artificially induced discontinuities have been compared and analysed relative to visual test results. The capability of the semi-automated eddy current system to detect discontinuities located on the inner surface of a 3.2 mm thick tube was studied.

Keywords: Flexible eddy current array, semi-automatic testing, seam thin-walled tube.

Introduction

Production of thin-walled pipe profiles is automated. Production consists of seam and seamless pipe profiles. Pipe profiles are released according to a product standard where there is a requirement for automated eddy current control of 100% of production output. Customers receive the product accompanied by a certificate of compliance with the product standard.
Implementation of automated test systems in combination with modern testing technologies lead to a testing time reduction, an increase in test efficiency and reliability of the results obtained, which results in an increase in the service life of the tested equipment or product [1÷3].
In this study, the capability of the semi-automated system used is demonstrated to perform sample incoming inspection of a thin-walled pipe profile, part of the production received by the customer. The thin-walled pipe profile inspected in this study was produced by Hus Ltd, Lom, Bulgaria, according to the requirements of product standard EN 10219-1 [10].
The purpose of the test is to verify the possibility of using a semi-automated eddy current system for incoming inspection by the customer of a part of the received production presenting thin-walled tube type made of ferromagnetic steel with one longitudinal seam.

1. Test method and technology

1.1. Test method

The eddy current test method is based on the induction of eddy currents in a test object by means of a probe coil or coils and observing the signal obtained by changing the induced eddy current field as a consequence of various changes in material. These changes can be in the geometry, electrical conductivity, magnetic permeability, thickness of base material or coating, surface roughness of test material or temperature anomalies, etc.

The method has the following limitations:

- only conductive materials can be inspected;
- surface must be accessible to the probe (test accessibility);
- surface finish and roughness can affect the result (inspectability);
- each separate location and size of the defect sought requires a separate reference sample with a discontinuity, necessary to set up the eddy current system;
- the depth of penetration of eddy currents is limited and depends on probe frequency and diameter, as well as on the electrical conductivity and magnetic permeability of tested material;
- discontinuities such as delamination that lie parallel to the propagating eddy current induced by the probe coil cannot be detected.

Knowing the method limitations, the requirements of technical specification to inspect a part of equipment or its product, and perform preliminary calculations for the characteristics of the eddy current field induced in the tested material, allow to choose a suitable device, probe and reference sample. This will lead to correctly selected operating characteristics for eddy current system setup, which in turn will increase the reliability of the obtained test results and the credibility of assessment for compliance with the technical specification.

1.2. Test technology

In this study, a flexible eddy current array probe is used operating in absolute mode. The testing of the welded joint and heat affected zone of steel tubular profiles is carried out by a semi-automated scanning system.

In the absolute mode of operation, the deviation of the measured quantity is measured relative to a reference point, which is determined in the process of setting up the system. This reference point is selected either by applying a certain voltage or after switching on an additional coil. This mode of operation is used to sort by size, by brand, and to evaluate the distribution of inhomogeneities in the test object. Absolute mode is more suitable to determine long linear discontinuities rather than circular ones.

Eddy current array probe (ECA) technology provides the ability to electronically power multiple coils placed side by side in the same probe. Data collection is done by multiplexing the eddy current coils in a certain way to avoid mutual inductance between the individual coils. The flexible eddy current probe of printed circuit board design is suitable for testing product of any surface curvature, it can also be used for flat surface testing.

Eddy current array probes have several advantages over other conventional eddy current testing technologies:

- faster testing time;
- a larger area is covered by one scan;
- products of complex shapes (other than flat surfaces) are inspected;
- display of a two-dimensional image in real time (view from above or C-scan);
- increased accuracy.

2. Preliminary theoretical calculations

2.1. Standard and effective penetration depth of the eddy currents induced in the material

On the basis of obtained experimental results and numerical studies in literature sources for the eddy currents depth of penetration, an analytical relation has been derived to determine the standard depth of penetration of eddy currents in electrically conductive materials [4 ÷ 6]. The analytical relation in the literature sources is given in different variations depending on the characteristics dimensions used. In this study, the following equation is used to facilitate the performed calculations:

$$\delta[mm] = \frac{661}{\sqrt{f.\mu_r}.\sigma} \qquad (1)$$

where f is working frequency of the probe in Hz; μ_r – relative magnetic permeability in dimensionless units; σ – electrical conductance in % IACS; δ [mm]- one standard depth of penetration of eddy currents in mm, for density of eddy currents I_x = 36.8 % of their density on tested material surface.

Eddy current density decreases exponentially with depth. The depth at which the eddy current density has decreased to 1/e or 36,8 % of the surface density is called a standard penetration depth. The word "standard" means the excitation of a plane-wave electromagnetic field within the test specimen.

The analytical equation for a standard eddy current field penetration depth is only true for infinitely thick material and planar magnetic fields for frequencies above 10 KHz. An infinitely thick test material is a specimen of thickness t > 5r, where r is coil radius. Plane field conditions are achieved by large diameter probes R > 10δ when testing flat products or long coils of length L > 5δ when testing pipe profiles. Real coils rarely meet these requirements, as they would have low sensitivity to defects. Using the standard depth calculated from the above equation makes it a test characteristic of the material.

Fig. 1 shows graphical dependence of the "standard" penetration depth calculated by equation (1) from frequency of eddy current field induced in the material. On the graph in the upper right corner, "mr" indicates the relative magnetic permeability. The calculations were carried out for a material of an electrical conductance of 13% IACS.

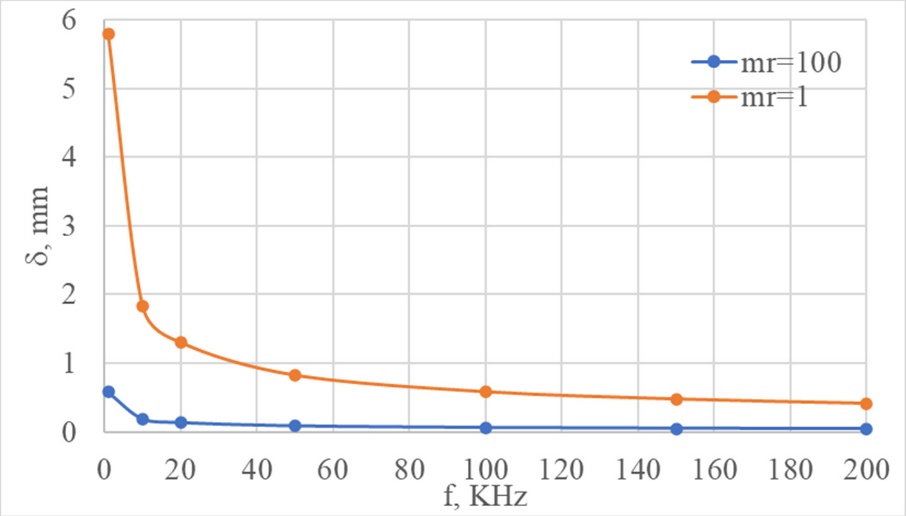


Fig. 1. Graphical dependence of a "standard" penetration depth from frequency of eddy current field induced in the material

In order to increase the standard penetration depth in ferromagnetic steel products, as can be seen from equation (1) and the graph in fig.1, it is necessary that the relative magnetic permeability tends to unity. Carbon unalloyed steels, such as the carbon structural steel studied in this paper, have a relative magnetic permeability of about 100 ÷ 200 and an electrical conductance of about 13 % IACS. Reducing the relative magnetic permeability to unity during inspection is achieved by magnetizing the material to saturation. From the graph in fig.1, one can see that the differences in the standard depth of penetration is ten times for frequency f=10 KHz. As frequency f increases, this difference decreases.

The effective penetration depth is determined depending on the standard penetration depth. The word “effective” means the depth of eddy current penetration, for which reliable inspection can be carried out depending on the test objectives.

When the goal is to determine the characteristic electrical conductance σ of the material then the effective depth of penetration is equal to three standard depths of penetration [8, 9]. According to the standard requirements, the inspection is considered reliable when the thickness of the tested material is less than an effective penetration depth.

When the purpose of the test is to determine a discontinuity located at a certain depth from the surface in the tested material, then the effective penetration depth is that, for which the discontinuity sought can be detected and sized. For this purpose, the test object must be inspectable. According to standard requirements, the test object is inspectable when the useful signal to noise ratio is 3:1. Under the condition that after the eddy current system has been adjusted, the noise on the screen during inspection is 10% FSH, and the maximum signal received during adjustment from a reference sample with an artificial surface discontinuity is 100% FSH, then the effective penetration depth must provide relative reduction of the eddy current density in the material up to 30%. The possibility to detect a discontinuity (sensitivity) depending on the tested object and the probe and operating characteristics (setting) used determine the effective depth of penetration for the inspection carried out.

2.2. Sensitivity to discontinuities (density of eddy currents)

Sensitivity to defects depends on the eddy current density at the location of the discontinuity. Although eddy currents penetrate deeper than a standard depth of penetration, they decrease rapidly with the depth. At two standard penetration depths (2δ), the eddy current density has decreased to $(1/e)^2$ or 13,5% of surface density. At three depths (3δ), the eddy current density is only to 5% of surface density. For thin plates or tube profiles, the current density drops less than the calculated from equation:

$$I_x = I_0 . e^{-x/\delta} \tag{2}$$

where I_x is the absolute change of density of eddy currents at depth x in A/mm^2, I_0 – absolute value of the density of eddy currents induced in the surface of a test material in A/mm^2, δ – standard depth of penetration in mm.

In fig. 2, a plot is given for the relative density changes of eddy currents in % from the material surface depending on the standard depth of penetration δ. The calculations were carried out according to equation (2) provided that the surface density of eddy currents I_0 was assumed to be one.

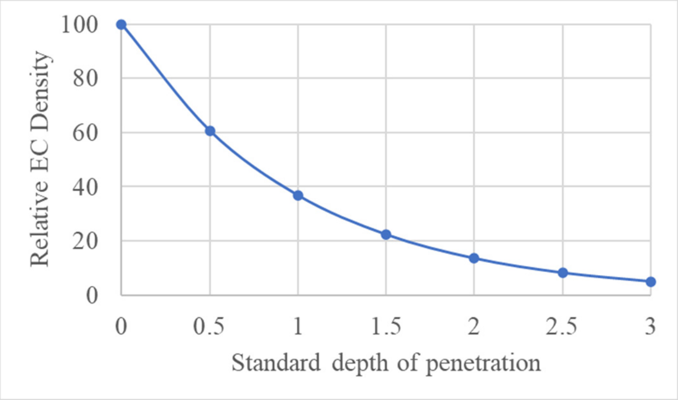


Fig.2 Relative density of eddy currents depending on the standard depth of penetration

According to the requirement to cover effective depth of penetration for reliable inspection for discontinuities in a material and results of the plot in fig. 2 the effective depth of penetration can be determined as equal to about 1.3δ. The determination of effective depth of penetration by the graph given in fig. 2 is carried out to the relative changes in the density of eddy currents. For practical purposes it is possible to use this approximate approach.

In fact, the effective depth determining method sensitivity is established by the absolute value of the density of eddy currents in A/mm^2. With a reduction in the working frequency, f, of a contact probe of "pancake" type coil, the area of eddy currents induced in the surface of the test material increases. This results in spreading the same quantity of eddy currents to a bigger area of the material. Therefore, with decreasing working frequency f, decreases also the absolute value of eddy currents induced in the surface layer of the material.

3. Test object

The test object is a pipe profile of 2 m length, of dimensions 48x3.2 mm. This pipe profile was made by company Hus LTD – Lom. The material is ferromagnetic sheet profile of non-alloy structural steel S235JRH. The pipe profile is produced by automated induction welding with longitudinal seam. The profile manufactured meets the requirements of EN 10219-1.

Several artificial discontinuities, through hole type and notch type, have been fabricated in the pipe profile. The through hole is made using a drill of 2.2 mm diameter. The surface notches are made using small milling machine of 0.4 mm thickness. Photograph of the fabrication of surface notch is given in fig. 3.

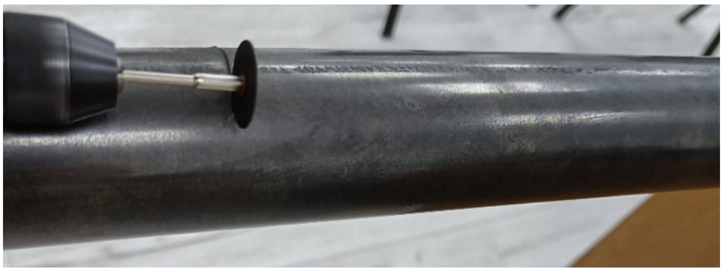


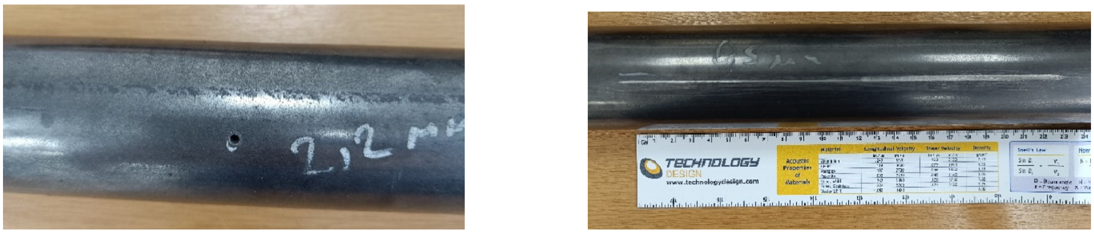
Fig. 3 Fabrication of surface notch type discontinuity using small milling machine

Five artificial discontinuities are fabricated of the following features:

- through hole type of diameter 2.2 mm (fig.4a);
- surface notch type (longitudinal) of length 180 mm, width 0.7 mm and depth 0.5 mm (fig.4b);
- surface notch type (transverse) of length 35 mm, width 0.7 mm and depth 0.5 mm (fig.4c on the left of the photograph);
- surface notch type (transverse) of length 27 mm, width 0.5 mm and depth 0.3 mm (fig.4c on the right of the photograph);
- surface notch type (transverse) of length 35 mm, width 0.7 mm and depth 0.5 mm (fig.4d).

Dimensions of the fabricated discontinuities were measured by a technical measuring tool calliper of ± 0.1 mm uncertainty.

Parts of test object with the discontinuities fabricated are shown in fig. 4.



a) through hole b) surface notch (longitudinal)

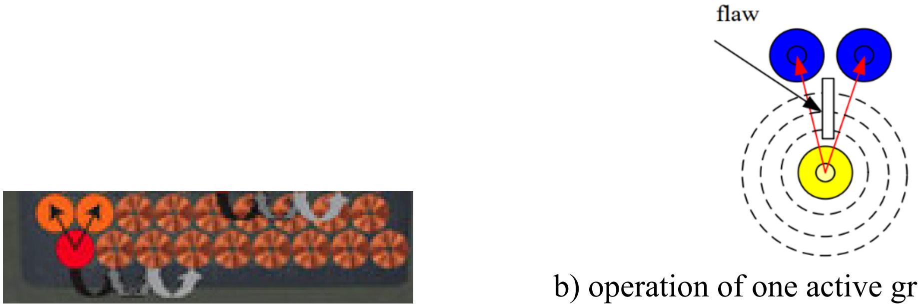
c) two surface notches (transverse) d) bottom notch (transverse)

Fig. 4. Parts of test object with the discontinuities fabricated in it.

4. Testing equipment

Eddy current unit OMNISCAN MX with ECA module to operate flexible eddy current array probe of model FBB-051-500-032 (reflection mode of operation) for testing pipes.

Eddy current unit is operated by built-in software. The test instrument is able to display collected data in three types of imaging: complex impedance plane, time from amplitude on X and Y и C-scans (view from the top).
The flexible eddy current array probe has 32 coils and 48 mm length. The coils are of "pancake" type and of 3 mm diameter. They are arranged in two rows linearly with shift between rows. The frequency range of the array probe is 80 KHz ÷ 3125 KHz. There is an encoder attached to the probe to localize the probe during testing. In absolute mode, the probe operates as follows: one coil generates eddy current, and two neighbour coils register it (reflection mode). Probe operation mechanism is given in fig.5.



a) coil operation sequence b) operation of one active group of three coils in reflection mode

Fig. 5 Operation mechanism of one active group of three coils for flexible eddy current array probe FBB-051-500-032 by OLYMPUS (EVIDENT)

Fig. 5a shows diagram of operation sequence of an eddy current array probe FBB-051-500-032 with an active group of three coils. The operation principle of the active group of three coils is given as diagram in fig.5b. The yellow coil generates magnetic field in red, this magnetic field induces eddy currents in test item indicated by black dashed line, the blue coils register the deviation of the eddy current induced in the material. In case of interruption of eddy currents, a deviation in the balanced signal is recorded. The deviation is maximum if the discontinuity interrupting eddy currents is parallel to the magnetic field and perpendicular to the eddy currents. For the first time this kind of eddy current array probe is developed and studied by a team with Vas. S. Cecco at Chalk River Nuclear Laboratories for internal tube inspection of steam generator tubes of part of Nuclear Power Plant in 1995 [7]. They also propose the mode of sequential excitation by three active coils, the one inducing eddy currents in material and the other two registering the eddy currents deviation as given in fig. 5b.

Photograph of a set of accessories for OD pipe eddy current inspection using flexible eddy current array probe FBB-051-500-032 is shown in fig. 6.

Fig. 6 Set of accessories for OD pipe eddy current inspection using flexible eddy current array probe FBB-051-500-032

5. Setting up the eddy current system

Before testing, the instrument characteristics are set for acceptance level E4H according to the requirements of EN ISO 10893-2 [11].

The flexible probe is placed on a plastic contact body suitable for the pipe diameter. It is attached to the flexible probe by teflon adhesive tape. Position is selected at 50 % horizontally and at 50 % vertically for the balancing point. The signal phase and amplitude are normalized. Normalization is carried out for the difference in signal obtained from non-conductive coating 0.1 mm thick applied on tested surface compared to the signal from test surface without non-conductive coating. Signals of all active groups are normalized (equalized) for phase 90 ° and amplitude 10 V, with probe working frequency 150 KHz. The setting is carried out by applying a voltage of 1 V to the coil inducing eddy currents in the test object. The setting is checked by artificial discontinuity of type through hole of diameter 2.2 mm. Images of the instrument display showing the setup check performed are given in fig. 7.

The C-scan in fig.7 illustrates the indication of through hole. Its amplitude is set up by vertical gain until 10 V FSH is reached, as seen from the image in the complex impedance plane on the left. Amplitude along the vertical peak-to-peak is 13 Vpp.

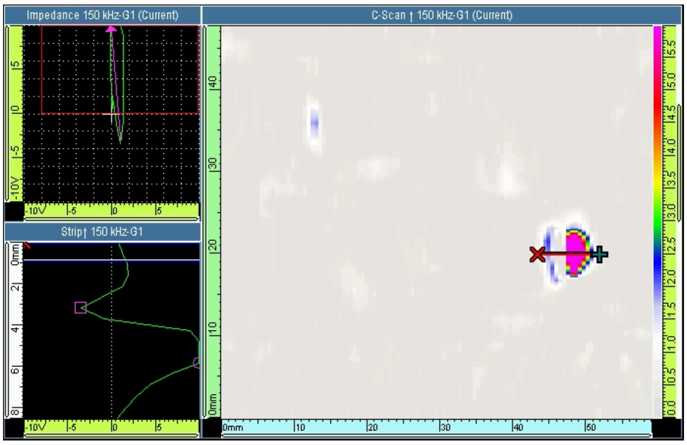


Fig. 7. Images of the instrument display showing the setup check performed

6. Testing

The pipe profile is tested using an eddy current probe FBB-051-500-032 operated by software built in the instrument. The testing is carried out in compliance with the requirements of standard EN 10219-1 (for determining the test method and acceptance level) and EN ISO 10893-2 (for testing technology). The probe and encoder are reset to a clean section, then scanning and data collection start. Data are collected and recorded in the instrument. During scanning the three types of images are displayed on the instrument screen. The collected information can be analysed at a later stage. The four discontinuities of type surface notch of different orientation relative to the probe and various position relative to probe contact surface (from the probe side and from the opposite side of the tested pipe) are tested.
Photograph of performing testing of two transverse notches on the pipe surface is shown in fig. 8.

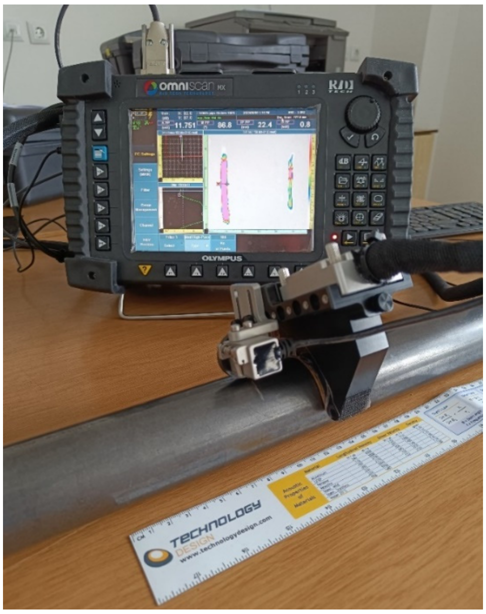
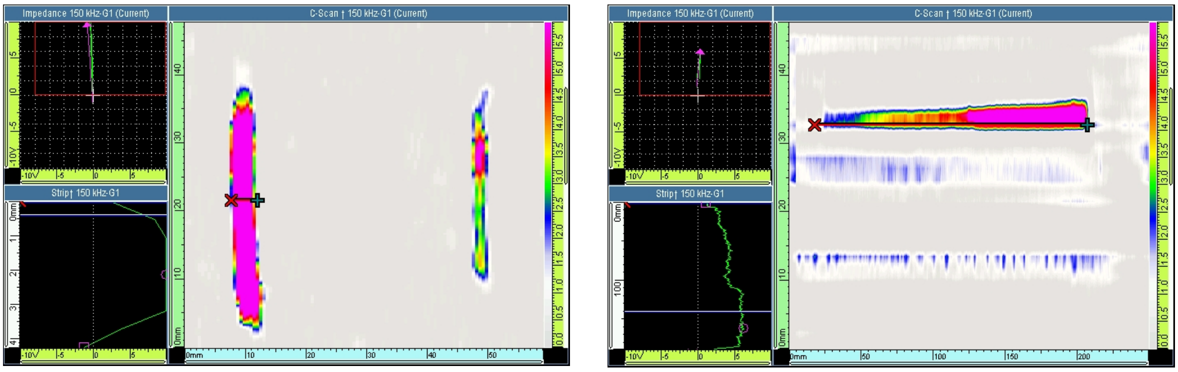


Fig. 8 Photograph of performing testing

On the instrument screen of the photograph in fig. 8, one can see the indications of both surface notches.

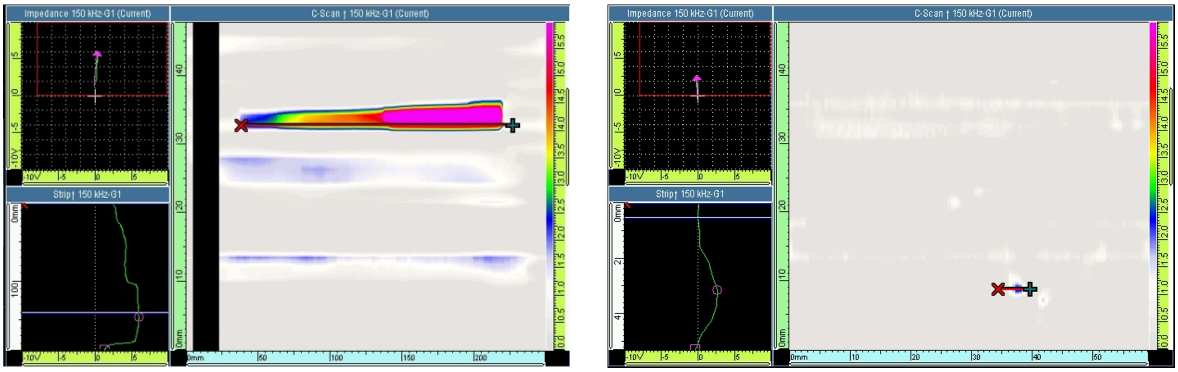
7. Results

The information collected during the scan is presented on the instrument screen in the three types of images. In fig. 9, a photograph is shown of the images of the information collected during scanning of the pipe in the section with notches.



a) indication of the two surface (transverse) notches, given in fig. 4c

b) indication of surface (longitudinal) notch, given in fig. 4b, without firter



c) indication of surface (longitudinal) notch given in fig. 4b, with low-pass median filter with 50 points.

d) display image of scanning bottom surface (transverse) notch from the opposite side to the probe contact, given in fig. 4d.

Fig. 9. Results of testings carried out on the eddy current instrument screen

On the right of fig. 9, a C-scan is shown of the tests performed on the notched section. Along X-axis of C-scan the light blue colour indicates the position of the probe along the tube axis recorded by the encoder. Along Y axis, the light green colour indicates the position of the probe coils along the pipe circumference from 0 mm to 48 mm. Indications of discontinuities in the C-scan are presented in a colour code from 0 V to 6 V, with colours ranging from grey for 0 V to red-pink for 6 V. The amplitude in the complex impedance plane is determined as maximum value by the balancing point in V or as maximum value peak-to-peak of the received signal in Vpp.

On the left of fig. 9, images of the complex impedance plane are given at the top, and below are images of the amplitude along Y-axis in the complex impedance plane from the distance marked by the cursor on the C-scan display.

8. Analysis of results

The C-scan of fig. 9, clearly shows an indication of the presence of a discontinuity in the tested section of the pipe for all discontinuities except for the one made on the inner surface of the pipe. The indications marked by the cursor are linear. The dimensions reported on the images of the instrument screen are given in table 1, and the characteristics of the received (collected) signals are given in table 2. The depth size is not determined by the image on the instrument screen. The depth can be determined indirectly by comparing the amplitude of the signal from the discontinuity with the amplitude of a signal from a reference discontinuity of known depth.

Table 1. Dimensions of indication and discontinuities in mm.

Photo of discontinuity	Dimensions of discontinuity, mm			Dimensions of indication from the instrument display, mm		
	Length, mm	Width, mm	Depth, mm	Length, mm	Width, mm	Depth, mm
Fig.4b	180	0.7	0.5	178	3 ÷ 4	-
Fig.4c (on the left)	35	0.7	0.5	34	4	-
Fig. 4c (on the right)	27	0.3	0.5	26	3	-
Fig.4d	35	0.7	0.5	-	-	-

Table 2. Characteristics of signals from indications received from the discontinuities

Photo of discontinuity	Amplitude, V	Amplitude peak-to-peak, Vpp	Phase peak-to-peak, pp
Fig.4b	13.5	11.3	94.5
Fig.4c (on the left)	17.5	15.7	86
Fig. 4c (on the right)	6.8	8.8	86
Fig.4d	-	-	-

The size of discontinuity determined from its indication on the instrument display images, given in table 1, shows a good coincidence with the indication results measured by a technical tool calliper.
The results in table 2 for amplitude of signal received from discontinuities of the same size (fig. 4b and fig. 4c on the left of the photograph) show that discontinuities oriented normal to the scanning direction are registered with a larger amplitude and better reliability compared to those oriented parallel to the scanning direction. The difference in the signal amplitude of the notch type discontinuity with the same width and depth and various orientation with respect to the scanning direction is about 4 V.
The tables show that the discontinuity of 0.5 mm width and 0.3 mm depth is reliably detected.
The bottom discontinuity cannot be detected under the current inspection conditions. It is required to reduce the operating frequency to about 10-20 KHz and magnetize the material to saturation during the inspection.

Conclusion

The test technology used reliably detects surface discontinuities imitating lack of fusion of a width of about 0.5 mm and a depth of 0.3 mm in the ferromagnetic pipe profile tested to acceptance level E4H according to the requirements of EN ISO 10893-2.

The sensitivity to the discontinuities detected increases when their length is oriented normal to the direction of magnetic field created by the coil inducing eddy currents in material part of an active probe FBB-051-500-032 group in the coil connection mode – reflection 2;
The sensitivity to discontinuities decreases with increasing depth. And for the technology used in this study with an operating frequency of 150 KHz it is about 0.1 mm and 1 mm with magnetization to saturation during the test.
In order to increase the depth of inspection for discontinuities in the tested pipe profile to its thickness of 3.2 mm, it is recommended to use lower frequencies in range of 10 ÷ 20 KHz and magnetization to saturation during the test.

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