

# Study on depth evaluation method for surface defects of austenitic stainless steel pressure pipes based on ECAT method

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**Abstract:** This paper aimed at the problem that it is impossible to evaluate the depths of the surface-breaking defect of austenitic stainless steel pressure pipes using the Magnetic Particle Testing(MT) and Penetration Testing(PT) methods. A quantitative method for measuring the depths of the surface-breaking defect of austenitic stainless steel pressure pipes based on eddy current array testing (ECAT) was proposed. According to the imaging features of defective ECAT correlation, by analyzing the change trend of the color, impedance amplitude and impedance phase of the C scanning, the corresponding relationship between the depth of the defect can be established, and finally, the effective evaluation of the depth of the opening defect on the surface of the material can be realized. Simulation and experimental results verify the effectiveness and reliability of the proposed method.

## 1. Introduction

Austenitic stainless steel pressure pipes are usually used to transport corrosive, toxic and flammable medium. Once an accident occurs, it will cause serious economic losses and bad effects. Stress corrosion cracking and pore erosion are the most common surface-breaking defect of the butt weld of austenitic stainless steel pressure pipe, which have a great threat to the safe use of pipelines in service.

At present, Magnetic Particle Testing (MT) and Penetrant Detection Testing (PT) are the preferred surface detection methods for detecting the surface-breaking defect on austenitic stainless steel weld surface. However, it can't achieve the quantitative depth of pipe defects. In 1986, In the international academic conference of the review of progress in quantitative NDE, *Auld* and *Marinov et al* presented the concept of eddy current array sensors, it marked the birth of the eddy current array testing(ECAT), which can directly detected without cleaning the surface of the workpiece, and effective testing the surface and near surface defects of the austenitic stainless steel. The C scan map can make the defects intuitionized, the phase of the impedance map can determine the true or false of the defect, and the strip map can make a preliminary quantitative analysis of the defects; In 1988, According to the relationship between the length of the crack and the diameter of the coil unit, *Chen* divided the crack into a long crack and a short crack, and established the relationship between the length of the crack and the amplitude curve of the detection signal, the depth of the crack and the phase curve of the detected signal under the condition of conventional eddy current testing(ECT); *Taniguchia* have carried out research on ECAT image, used image processing algorithm to determine the specific location of defects. *He* was simulated the mutual inductance between the coil units of the eddy current



array sensor using the three-dimensional finite element method; *Liu* established a mapping relationship between the crack length, depth and the time domain characteristics of the detected output signal in the light of the transmitting and receiving eddy current array sensor; *Machand* designed a flexible eddy current array probe which used to detect the complex surfaces samples, the probe was very sensitive to micro defects, but no public quantitative test results; *Lim* used the mechanical and electrical impedance (EMI) technology to monitor the three stages of fatigue crack, this technology used the PZT material as the exciting and vibration sensor, and can monitor fatigue cracks at high sensitivity and high precision, but can't quantify and visualize the position of the crack; *Hughes* found that the detection frequency of the probe was close to its resonant frequency, which can effectively improve the detection sensitivity of eddy current testing; *Xie* developed a new type of flexible planar eddy current sensor array to detect the micro crack length of the key parts of the aircraft. it can measure the fatigue crack length quantitatively, and the detection precision can reach to less than 0.2mm; *Li* proposed an annular eddy current array sensor crack monitoring scheme, which can implement quantitative monitoring of cracks. This method can improve the detection sensitivity of the sensor, but it has limitations on the quantitative discrimination of the deeper defects and defects on the near surface.

A quantitative method for measuring the depths of the surface-breaking defect of austenitic stainless steel pressure pipes based on eddy current array testing (ECAT) is proposed. According to the imaging features of defective ECAT correlation, by analyzing the change trend of the color, impedance amplitude and impedance phase of the C scanning, the corresponding relationship between the depth of the defect can be established, and finally, the effective evaluation of the depth of the opening defect on the surface of the material can be realized

## 2. Detection Principle

Eddy Current Array Testing (ECAT) is a new branch of Eddy Current Testing (ECT). By studying the interaction between the defects in the material and the electromagnetic field, the size and distribution of the scattered field were calculated according to the known source, and then the detection signal can accurately evaluated.

The specific detection steps are as follows: take the detection coil with alternating current closed to the measured object. Due to the effect of the magnetic field, the eddy current will be induced in the measured object, the amplitude, phase and flow form of the eddy were affected by the conductivity and defects of the specimen, and also formed a magnetic field, which will change the impedance of the detection coil in turn. Therefore, by detecting the change of coil impedance, it could determine whether there were defects or not in the measured objects. The electromagnetic field induced by the interaction between eddy coils and conductor specimens was based on the *Maxwell* equation:

$$\begin{cases} \nabla \times H = J + \frac{\partial D}{\partial t} \\ \nabla \times E = -\frac{\partial H}{\partial t} \\ \nabla \cdot D = \rho \\ \nabla \cdot B = 0 \end{cases} \quad (2-1)$$

As  $B = \mu H$ ,  $D = \varepsilon E$ ,  $J = \sigma E$ ,  $\sigma$  is conductivity,  $\mu$  is magnetic permeability,  $\varepsilon$  is permittivity,  $J$  is current density,  $E$  is electric field intensity,  $H$  is magnetic field intensity,  $B$  is magnetic induction intensity,  $D$  is electric flux density,  $\rho$  is free charge density.

The total vector magnetic potential  $A^T$  produced by the eddy current array sensor was:

$$\begin{cases} A_{x(x,y,z)}^T = \sum_{k=1}^{n_\mu} \text{sign}(I^{(k)}) \frac{oy^{(k)}}{r^{(k)}} A^{(k)}(r^{(k)}, z) \\ A_{y(x,y,z)}^T = \sum_{k=1}^{n_\mu} \text{sign}(I^{(k)}) \frac{x-ox^{(k)}}{r^{(k)}} A^{(k)}(r^{(k)}, z) \\ A_{z(x,y,z)}^T = 0 \end{cases} \quad (2-2)$$

$n_\mu$  is the number of coil units of the eddy current array sensor,  $(ox^{(k)}, oy^{(k)})$  is the coordinates

of the central axis of the coil unit  $k$  in the  $XOY$  plan of the rectangular coordinate system,  $r^{(k)}$  is the distance between the central axis of the coil unit  $k$  and the calculated point  $(x, y, z)$ ,  $\text{sign}(I^{(k)})$  is the direction of current in the coil unit  $k$ ,  $A^{(k)}(r^{(k)}, z)$  is the vector magnetic potential of the coil unit  $k$  in  $(r^{(k)}, z)$ .

Finally, The impedance of each coil unit in the field can be calculated according to the total vector magnetic potential of the eddy current array sensor:

$$Z(j\omega) = -n_c \int_0^{2\pi} d\theta \int_{r_1}^{r_2} r dr \int_{l_1}^{l_2} \frac{E^T(Q, j\omega) \cos\varphi}{I(j\omega)} dz \quad (2-3)$$

$E^T(Q, j\omega)$  is electric field intensity,  $\varphi$  is the angle between the electric field intensity and the current density in  $Q \in V_c$ .

### 3. Simulation

In order to verify the feasibility of the proposed method, the *ET* module of *CIVA* software was used to simulate the impedance characteristics of the typical defect depth (crack, hole corrosion). The thickness of the workpiece is  $5\text{mm}$ , the material is 304L stainless steel, the conductivity is  $1.39 \text{MS}\cdot\text{m}^{-1}$ , and the relative permeability is 1. The unit type of the flexible eddy current array probe coil is *Spiral coil*, the outer diameter of the coil  $D$  is  $3.1\text{mm}$ , the height  $H$  of the winding and the thickness  $E$  are  $0.04\text{mm}$ , and the number of coil turns is 15.

Stress corrosion cracking is one of the common crack defects of the austenitic stainless steel butt joint. The surface opening groove was used to simulate the surface-breaking defect in this paper, by analyzing the changes of the color, impedance and impedance phase of the C scanning corresponding to the depth of the groove, and achieved the impedance characteristics simulation of the crack defects.

In order to verification the influence of the impedance characteristics by the depth of the groove, a groove with the same length and width and different width was used in CIVA model, shown in Figure 1, and the size of each grooves is shown in Table 1.



Fig 1. The response mode of groove depth

Table 1. The size of each grooves

Groove number	length(mm)	width (mm)	depth (mm)
1#	10	0.2	0.2
2#	10	0.2	0.5
3#	10	0.2	1.0
4#	10	0.2	2.0
5#	10	0.2	3.0

The excitation frequency of the coil is  $500\text{kHz}$ , the exciting current is  $500\text{mA}$ , and the lift off height of the coil is  $0.2\text{mm}$ . The simulation result was shown in Figure 2. As known in Figure 2, as the depth of the grooves became larger, the color of C scan imaging was from shallow to deep, the amplitude of impedance became large, the impedance phase changes were as same. The depth of the groove mainly affects both by the amplitude impedance and impedance phase. Therefore, C scan imaging color, impedance amplitude and impedance phase are important indicators to evaluate defect depth.

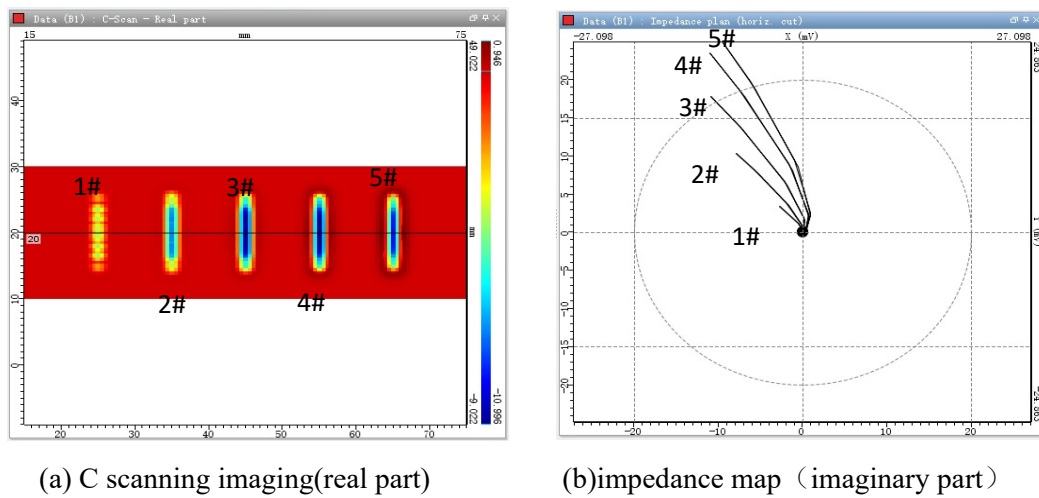


Fig 2. The impedance characteristics simulation result of the grooves with different depths

#### 4. Experiment

The test system adapts a self-built eddy current array automatic scanning experimental system. The system consists of automatic scanning system, eddy current array detection system and test piece. The automatic scanning system includes industrial control computer, display, control cabinet and scanning arm; Eddy current array detection system includes main engine, probe device, encoder and so on. As shown in Figure 3. The test material used 304 stainless steel thin plate (thickness  $T=1.1\text{mm}$ ). the reference body of stress corrosion cracking is the groove.



Fig 3. Test system

Fig. 4 was the result of eddy current array scanning of the groove. As shown from Figure 4, the C scan of the groove present as a strip, the color of the C scan dilute with the decrease of depth, and the vertical component of the impedance amplitude in the strip map decreases with the decrease of the depth. The impedance amplitude and impedance phase change regularly with the depth of groove.

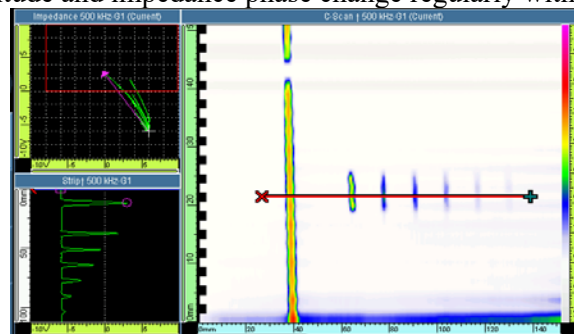


Fig 4. ECA data of grooves

Table 2 lists the relation between the size of groove and the impedance amplitude and phase. Figure 5 shows the relation diagram of the depth-impedance amplitude and phase of the groove. As shown in tables 2 and 5, the impedance amplitude and phase of the groove are not only related to the depth, but also to the size of the defects. When the length and width of the grooves are constant, the impedance amplitude and phase increase with the increase of groove depth. Therefore, when evaluating the crack correlation display or strip correlation display, the reference body should select the width similar to the actual defect.

Table 2. the relation between the size of groove and the impedance amplitude and phase

The size of groove	impedance amplitude	impedance phase
5×0.3×1.1	8.08	72.10
5×0.3×0.9	5.74	70.30
5×0.3×0.7	4.78	65.60
5×0.3×0.4	3.05	60.30
5×0.3×0.2	1.54	57.60
5×0.3×0.1	0.63	54.20

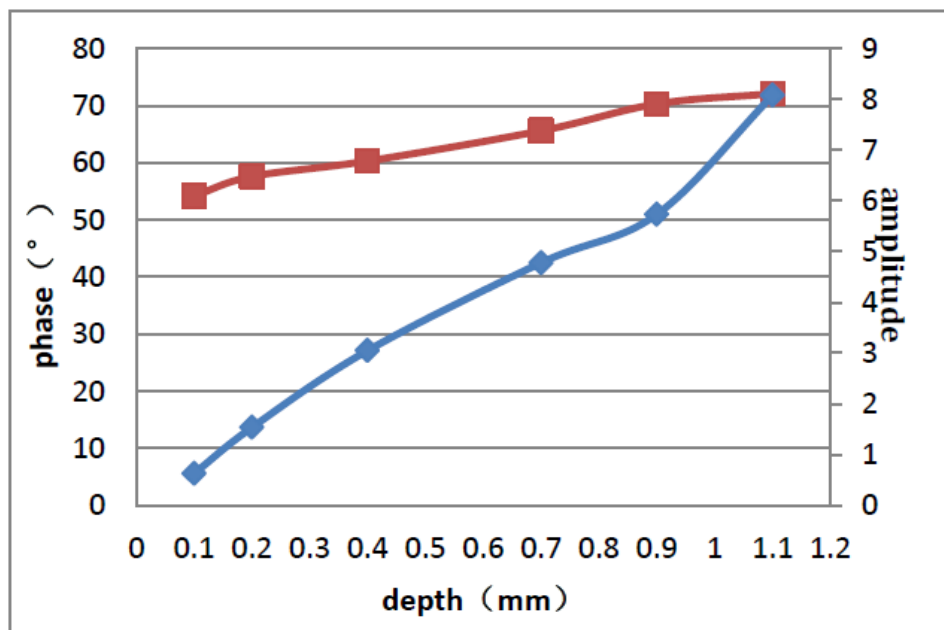


Figure 5 .The relation diagram of the depth-impedance amplitude and phase of the groove

## 5. conclusion

A quantitative method for measuring the depths of the surface-breaking defect of austenitic stainless steel pressure pipes based on eddy current array testing (ECAT) is proposed. Through simulation and experimental research, the imaging features of the ECAT related display of the crack defects of the austenitic stainless steel butt joints was analyzed in detail. by analyzing the change trend of the color, impedance amplitude and impedance phase of the C scanning, the corresponding relationship between the depth of the defect can be established, and finally, the effective evaluation of the depth of the opening defect on the surface of the material can be realized. Simulation and experimental results verify the effectiveness and reliability of the proposed method.

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## Reference

- [1] Jun J, Hwang J, Lee J. Quantitative Nondestructive Evaluation of the Crack on the Austenite Stainless Steel Using the Induced Eddy Current and the Hall Sensor Array[C]. Instrumentation and Measurement Technology Conference. Warsaw: Poland, 2007. 1-6.
- [2] Zhou Z X, Jin S S, Liu C L et al. Stress corrosion cracking and prevention of austenitic stainless steel pressure pipes[J]. Physical and chemical test (physical division), 2015,51(10)
- [3] Li T Y, Hu B, Dai H B et al. Comparison of stress corrosion cracking detection techniques for austenitic stainless steel pipes[J].NDT, 2016,38(11):74-78
- [4] Chen X D, Wang B, Guan H W et al. Analysis of the current situation and defects of pressure vessels and pipes used by petrochemical enterprises in China and Countermeasures for failure prevention[J], Pressure vessel, 2001, 18(5):43-53
- [5] Song X G, Zhang X Q, Chan Y Y et al. Statistical analysis of corrosion failure cases for pressure equipment [J]. material engineering, 2004, (2): 6-9
- [6] Fan Q Q, Hua L. 2205 factors affecting corrosion behavior of duplex stainless steel [J]. corrosion science and protection technology. 2014, 26(2):178-182
- [7] Leclerc R, Samson R. Eddy Current Array Probe for Corrosion Mapping on Ageing Aircraft[C]. Review of Progress in Quantitative NDE. New York, 2000, 19: 489-496
- [8] Zilberstein V, Goldfine N, Washabaugh A et al. The Use of Fatigue Monitoring MWM Arrays in Production of NDI-Standards with Real Fatigue Cracks for Reliability Studies[C]. 16th World Conference on NDT, Montreal, Canada, 2004: 1-8
- [9] Marnov S G. Theoretical and Experimental Investigation of Eddy Current Inspection of Pipes with Arbitrary Position of Sensor Coils[C]. Review of Progress in Quantitative NDE, New York, 1986, 5: 225-232.
- [10] Chen D Z. Research on numerical simulation and signal processing in eddy current nondestructive testing [D]. Xi'an: Xi'an Jiao Tong University, 1998:32-42
- [11] Taniguchia T, Nakamura K, Yamada S, et al. Imag Processing in Eddy-Current Testing for Extraction of Orientations of Defects[J]. International Journal of Applied Electromagnetics and Mechanics, 2001,14:503-506
- [12] He Y B, Shao Y G. Research on crack characteristic quantity based on array eddy current technology [J]. sensor and micro system, 2010,29(2):80-82
- [13] Liu B, Luo F L, Hou L J. Research on the method of crack feature extraction by eddy current array [J]. Journal of instrumentation, 2011,32(3):654-659
- [14] Marchand B, Decitre J M, Sergeeva C et al. Development of flexible array eddy current probes for complex geometries and inspection of magnetic parts using magnetic sensors[C]. In Proceedings of the 39th Annual Review of Progress in Quantitative Nondestructive Evaluation. Denver:USA, 2012. 488-493.
- [15] Lim Y Y, Soh C K. Electro-mechanical impedance (EMI)-based incipient crack monitoring and critical crack identification of beam structures[J].Research in Nondestructive Evaluation, 2014, 25(2), 82-98
- [16] Hughes R, Fan Y, Dixon S. Near electrical resonance signal enhancement (NERSE) in eddy-current crack detection[J], NDT&International, 2014,66(3):82-89
- [17] Xie R F, Chen D X, Pan M C, et al. Fatigue Crack Length Sizing Using a Novel Flexible Eddy Current Sensor Array[J].Sensors, 2015, 15(12):32138-32151
- [18] Li P Y, Li C, He Y T, et al. Sensitivity boost of rosette eddy current array sensor for quantitative monitoring crack[J]. Sensors and Actuators A: Physical, 2016,246:129-139
- [19] Zaoui A, Feliachi M, Doirat V et al. A fast 3D modeling of arrayed eddy current sensor[C]. Proceeding of the 12th Biennial IEEE Conference Electromagnetic Fields Computation,

CEFC,2006.66

- [20] Zaoui A, Menana H, Feliachi M, et al. Generalization of the Ideal Crack Model for an Arrayed Eddy Current Sensor[J], IEEE Transaction on Magnetics, 2008, 44(6):1638-1641