Development of Ultrasonic Transducer Testing

Austenitic Stainless Steel Weld

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Abstract

A transducer, as applied to ultrasonic testing, is the means by which electrical energy is converted into acoustic energy and back again. The device, adapted for UT, has been called a probe, a search unit, and a transducer. Due to inner special structure, the ultrasonic testing of the coarse grains material such as welds in austenitic stainless steel is very difficult and demands a special transducer. The vibration equivalent circuit and vibration equation of the ultrasonic transducers for such usage are analyzed and main factors influencing them are studied at length in this paper. Proved through the theory analysis, a transducer with brand-band and higher sensitivity and resolving should be designed followed as acoustic matching between piezoelectric crystal and load, electric-acoustic matching between the crystal and acoustic receiver, as well as the high resolving power. Finally, the transducers meeting testing demand are developed. The transducer's initial pulse width is 1.5 cycles and quality factor in -6db is 1.

Keywords: Coarse Grains Material, Transducer, Ultrasonic Testing(UT)

1. Foreword

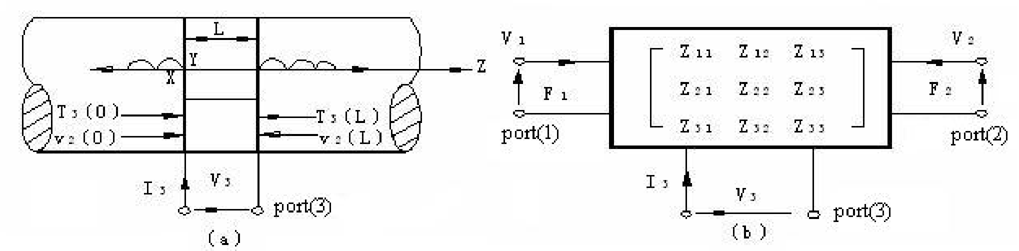
Using Ultrasonic Testing (UT) technique inspecting austenitic stainless steel weld which is widely used in petrochemical and nuclear power industries is a very applicable and economical method. Because inside grains in austenitic stainless steel are too coarse for general ultrasonic probes, higher attenuation and less penetration as well as clutter echoes are generated when the wave propagates in the material[1]. And then, detectability of discontinuities in these material gets lower. So, researching and developing a new transducer for these material testing is very urgent.

2. Requirement on transducer testing coarse grain material

The coarse-grained and inhomogeneous structure in austenitic stainless steel weld results in severe scatterance and attenuation of ultrasonic energy. In order to increase SNR (Signal to Noise Ratio) for farther enhancing the testing sensitivity and detectability of defects, the incident acoustic wave should be low-frequency, long-wavelength, which behaves lower attenuation, more penetration and higher SNR. In addition, pulse duration cycles also evidently affect the SNR of defect-echoes. Commonly, the more short duration, the better SNR is[2]. In a word, to successfully inspect austenitic stainless steel, the transducers with low-frequency, short-duration pulses, high-sensitivity and high-resolution should be used.

3. Equivalent circuit and transient characteristic analysis on piezoelectric transducer

Figure 1 is the geometrical model for researching piezoelectric transducer suppose that the wafer is completely vibrated along Z axis. Accordingly, its Mason equivalent circuit is illustrated in figure 2[3].



(a) Geometrical model for transducer

(b)Equivalent circuit with acoustic ports(1 and 2)and electric port(3)

Figure 1 Wafer vibrated in terms of thickness mode

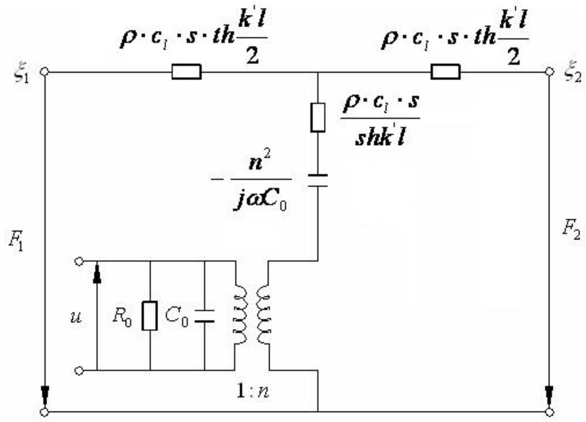


Figure 2 Mason equivalent circuit of piezoelectric crystal

Piezoelectricity equation in figure 1 is below:

$$\begin{cases} S_3 = s_{33}^D T_3 + g_{33} D_3 \\ E_3 = -g_{33} T_3 + \beta_{33}^T D_3 \end{cases}$$

Where

S_3 is the strain on orientation “3”

E_3 is the electric field intensity on orientation “3”

D_3 is the Electric displacement vector on orientation “3”

T_3 is the stress on orientation “3”

β_{33}^T is inverse dielectric constant on orientation “3”while the stress is constant

s_{33}^D is elastic flexible coefficient on inverse to orientation “3” while the electric displacement is constant

g_{33} is piezoelectric voltage constant on orientation “3”.

According to Newton's 2nd law, we can deduce the vibrating equation as follows:

$$\rho \frac{\partial^2 \xi}{\partial t^2} = \frac{\partial^2 T}{\partial Z^2}$$

Inside piezoelectricity crystal, electric field intensity is constant, that is div·D=0. So, the vibrating equation is given:

$$\rho \frac{\partial^2 \xi}{\partial t^2} = \frac{1}{s_{33}^D} \bullet \frac{\partial^2 \xi}{\partial Z^2}$$

Due to boundary condition: if Z＝0,then F＝F_1 , $\xi = \xi_1$;

if Z＝l, then F＝F_2, $\xi = \xi_2$.

Having regarded medium wastage, we can obtain following key:

$$\begin{bmatrix} F_1 \\ F_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} \frac{\rho c_l S}{thk'l} & \frac{\rho c_l S}{shk'l} & \frac{g_{33}}{j\omega s_{33}^D} \\ \frac{\rho c_l S}{shk'l} & \frac{\rho c_l S}{thk'l} & \frac{g_{15}}{j\omega s_{33}^D} \\ \frac{g_{33}}{j\omega s_{33}^D} & \frac{g_{33}}{j\omega s_{33}^D} & \frac{1}{j\omega C_0} \end{bmatrix} \bullet \begin{bmatrix} v_1 \\ v_2 \\ I_3 \end{bmatrix}$$

Where

F_1 and F_2 were the forces acting on the two faces of crystal respectively

V_s is voltage between the two poles of crystal

C_0 is static capacitance of crystal

ρ is density of crystal

c_l is ultrasonic wave traveling velocity in crystal material

S is effective polarized area of crystal

l is thickness of crystal

v_1 and v_2 were particle vibrating velocities on the two faces of crystal respectively

ξ_1 and ξ_2 were particle displacement on the two polarized sides of crystal respectively.

Using Mason equivalent circuit and performing numerical calculation with computer are more handy way in transient characteristic analysis of piezoelectricity transducer. This method not only analyzes configuration parameter and exciting resource and crystal's influence on the transient characteristic, but also carries out simulating design for transducer utilizing computer.

4. Development of the transducers

Transducer with good performance should be designed according to these aspects such as acoustic matching between piezoelectric crystal and load, electric and acoustic matching between crystal and transmitter and receiver device, improving resolving power. The transducer made according to this design will achieve the level of broadband, high sensitivity and high resolving power.

The designing parameters relating to crystal, backing material and front matching layer can be calculated in theory, through analyzing transient characteristic of transducer. Choosing the sound piezoelectric material can ensure the high sensitivity and broadband of transducer. Choosing the sound backing material and front matching layer whose acoustic impedance close to crystal can ensure the short-duration pulses and high resolving power of transducer. As damping block, backing material can restrain radial vibration of transducer besides affecting on ultrasonic pulse-width. As coupling layer between crystal and item, the frontal matching layer must be carefully designed on its thickness and acoustic impedance.

4.1Piezoelectric crystal

The sensitivity and bandwidth of transducer depend on piezoelectric material. The parameters determining the transducer's sensitivity include piezoelectric stress constant "e" and electromechanical coupling coefficient "K_t". Bigger value of "e" implies that smaller voltage on crystal can bring bigger vibrating amplitude, namely, the transmitting performance of crystal is better. Bigger value of "K_t" implies higher conversion-efficiency between acoustic and electric energy. So, the piezoelectric ceramic with bigger "e" and "K_t", can ensure higher testing sensitivity.

Because the transducer's frequency is determined by the thickness of crystal element, the wafer thickness must be accurately regulated for proper frequency.

4.2 Acoustic impedance in backing material

The backing material plays a very crucial role during controlling the bandwidth and pulses duration of transducer. Analyzing the equivalent circuit on transmitting, the energy vibrating on the crystal back is completely absorbed in backing material while acoustic impedance is identical between backing material and crystal. In this wise, transmitting pulses duration of transducer is the shortest. Usually, the acoustic impedance of piezoelectric crystal is about （30～36）$\times 10^6$ Pa·s/m, whereas the typical impedance of backing material is no more than 24×10^6 Pa·s/m.

4.3Front matching layer

Good matching layer can couple crystal well to the test item, and prevent crystal from being worn out. In contact method inspection, the acoustic impedance of matching layer (z) should be fit to the impedance of crystal (z_1) and item (z_2) and the optimal relation among them is $z = \sqrt{z_1 \bullet z_2}$ [4]. Here, the thickness of matching layer is a quarter of wavelength and the transmitting energy is the biggest.

4.4Performance testing on transducer

The transducer's performances include its initial pulses width, center frequency, sensitivity, resolving power and upper and lower dead-zone etc. The duration of initial pulses is mainly determined by vibrating resource, partly by backing material and frontal matching layer. The width of initial pulses is always designed to very narrow because it determines transducer's dead-zone size and depth resolution. The center frequency is decided by the crystal thickness and it indicates the sensitivity and ultrasonic attenuation in medium. A rule of thumb for the highest sensitivity in UT is λ/2 (λ is a wavelength) because of diffraction effect and energy attenuation rapidly increasing with frequency. The frequency of transducer applying to high attenuating material such as austenitic stainless steel weld will be adequately small on precondition of defect's being detected, therefore, the ultrasonic propagation in item is guaranteed.

Figure 3 is waveform and frequency-spectrum of the transducer developed in our research. The center frequency is 0.88MHz and the initial pulse width is just 1.5 cycles. The quality factor in -6db is 1. So, the transducer ensures low attenuation and high resolution and detectability of defects.

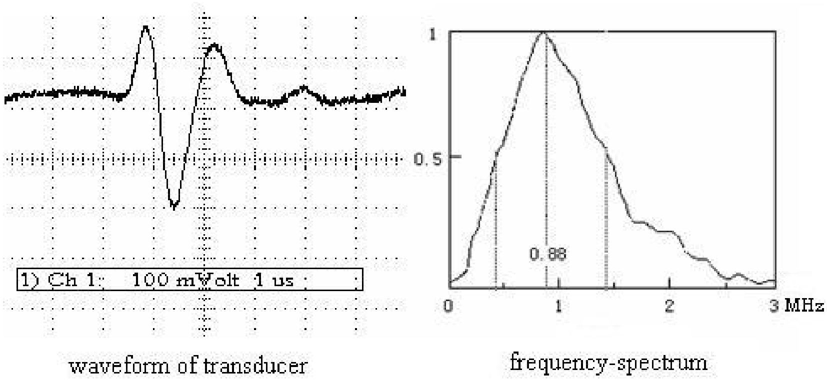


Figure 3 Performance of developed transducer

5. Conclusion

The inspection and estimation on coarse grains material such as austenitic stainless steel weld receive much recognition in the NDT's world and the demand on material evaluation is increasingly improved. The common UT is an available method just advancing higher requirement on transducer used in. The transducer meeting application has be developed through analysis on vibrating model and transient characteristic in this paper and is successfully used in the material testing.

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