オーステナイト系ステンレス鋼溶接部割れに対する超音波探傷試験の検出解析確率

Probability of detection analysis of ultrasonic NDT applied to austenitic stainless steel welds

青島科技大 東北大学大学院	孟　思琪	Siqi　MENG	Non-member
東北大学大学院	宋　海成	Haicheng　SONG	Member
東北大学大学院	遊佐　訓孝	Noritaka　YUSA	Member
東北大学流体研	内一　哲哉	Tetsuya　UCHIMOTO	Member
東北大学流体研	高木　敏行	Toshiyuki　TAKAGI	Member
青島科技大	凌　元錦	Yuanjin　LING	Non-member
東北大学大学院	橋爪　秀利	Hidetoshi HASHIZUME	Member

Abstract

This paper evaluated the probability of detection(POD) of austenitic stainless steel welds from the viewpoint of ultrasonic testing. It presents results of simulation-based POD curves of ultrasonic NDT. The simulation model based on a three-dimensional Finite Element Method (FEM) is presented to perform the data generation. Results of conventional POD considering the depth of flaw are given and the requirement of taking the length of flaw into considered is determined.

Keywords: ultrasonic testing, nondestructive inspection, numerical simulation, finite element method, POD analysis

1. Introduction

Ultrasonic testing is a typical nondestructive testing (NDT) method. Detecting flaws by non-destructive testing before they grow to a certain size is a key issue for assuring the structural integrity of nuclear power plants.

Because there are various factors affecting the results of NDT, the reliability of NDT is characterized by a probability to detect a flaw, and the probability of detection (POD) analysis is considered to be the standard method for estimating the reliability.

There are two conventional approaches to evaluating POD: hit/miss analysis and $\hat{a}$ vs a analysis [1]. The latter, $\hat{a}$ vs a analysis is more widely used and it can provide more information for the POD analysis. In the $\hat{a}$ vs a analysis, data are recorded as an amplitude of the response signal from a flaw and whether or not a flaw is detected is evaluated depends on whether or not a signal exceeds a defined decision threshold [2]. One of the most serious problem with the conventional POD used to describe the reliability of NDT is that it expressed a flaw using one parameter. Consequently, it suffers from large uncertainty when applied to general structures where variety of flaws would appear.

On the basis of this background, this paper focuses on the POD model developed to discuss the reliability of ultrasonic NDT, showing the capability of detecting defects in the austenitic stainless steel weld.

2. Materials and methods

2.1 Simulation model

Figure 1 illustrates a three-dimensional finite element simulation model to gather ultrasonic signals due to a crack

連絡先: 東北大学大学院工学研究科量子エネルギー工学専攻　〒980-8579 宮城県仙台市青葉区荒巻字青葉6-6-01-2
E-mail: meng.siqi.s4@dc.tohoku.ac.jp

appearing in a stainless steel weld for this study. A semi-elliptic flaw is embedded in the weld of stainless steel plate requiring to be detected. An angular beam transducer is used to generate and receive ultrasonic waves, the waves reflected from flaw carried the information needed to be analyzed. In order to prevent reflections from the edges of the model, absorption bands and viscous boundaries are provided on the four sides of the area under analysis: left, right, front and back.

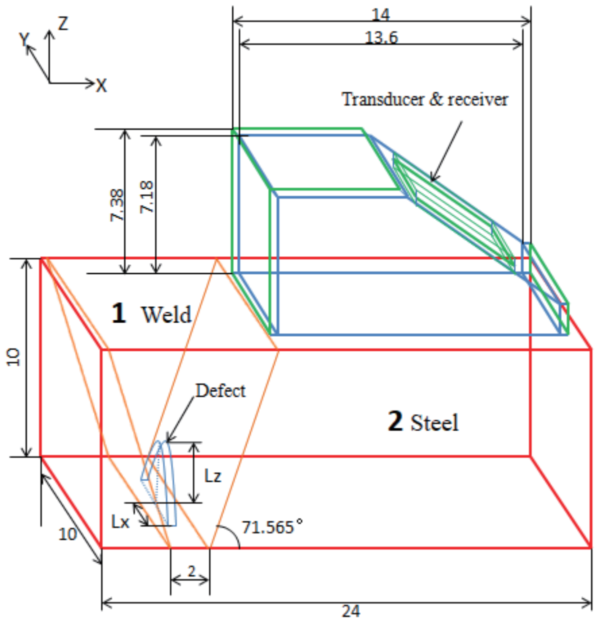

Fig.1 Appearance of 3D simulation model (units : mm)

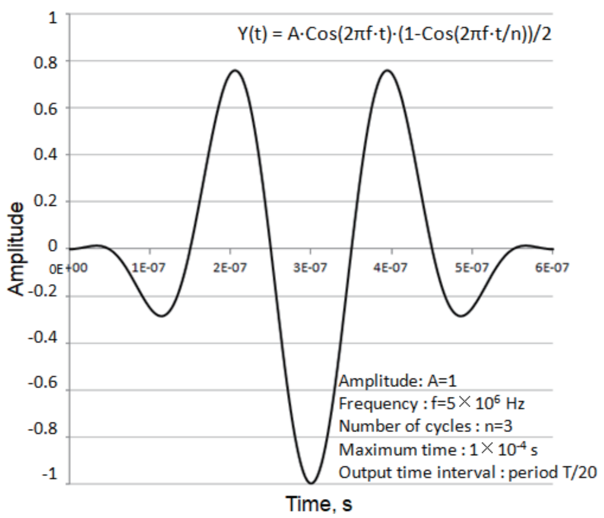

Fig. 2 Settings of input waveform

Table 1 Parameters of flaw size used in the simulation

Parameter	Value
Depth of flaw (Lz)	0.1, 0.3, 0.5, 1, 2, 3, 5, 7, 9 mm
Half length of flaw (Lx)	0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4.5 mm

Table 2 Parameters used in the simulation

Parameter	Value
Sound velocity of longitudinal wave in transducer	2730 m/s
Sound velocity of transverse wave in transducer	1430 m/s
Density of transducer	1.18 g/cm^3
Sound velocity of longitudinal wave in steel	5900 m/s
Sound velocity of transverse wave in steel	3200 m/s
Density of steel	7.8 g/cm^3
Density of weld	7.9 g/cm^3

The parameters of the flaw is presented in Table 1.Table 2 lists parameters used in the simulations; the waveform the transducer generates is shown in Figure 2.

2.2 Data analysis to estimate the POD curve

Amplitude of ultrasound reflected from the crack was set as the signal response $\hat{a}$, the depth of flaw was selected as the defect size a. Signals obtained by the numerical simulations were polluted with 10% white noise to simulate experimental noise.

In the signal response data analysis, it is assumed that the signal response $\hat{a}$, has a linear relationship with defect size a as :

$$\ln(\hat{a}) = \beta_0 + \beta_1 \ln(a) + \varepsilon \quad (1)$$

where ε is a normally distributed error term, $\varepsilon \sim N(0, \tau)$.

The unknown parameters in eq. (1), (β_0, β_1, τ), are estimated by the Maximum Likelihood Analysis to maximize log- likelihood function is written as:

$$\log L = \sum_{i=1}^{N} \Big[H[c - y_i]_i \log\Phi\left(\frac{c - x'_i\beta}{\tau}\right) + H[y_i - b]_i \log\Phi\left(\frac{x'_i\beta - b}{\tau}\right) + \left(1 - H[c - y_i]_i - H[y_i - b]_i\right)\left(\log\phi\left(\frac{y_i - x'_i\beta}{\tau}\right) - \log\tau\right)\Big] \quad (2)$$

where c is the left censor, b is the right censor, the subscript i = 1,…, N indicates the observation, $y_i = \ln \hat{a}_i$, $x'_i = \ln(a_i)$, Φ and ϕ denote the cumulative distribution function and probability density function of the standard normal distribution. H_i is Heaviside function. The value of b and c used in this study are 0.045 and 0.25, respectively.

The POD(a) function is calculated as [3] :

$$POD(a) = 1 - \Phi\left[\frac{\ln(\hat{a}_{decision}) - (\beta_0 + \beta_1 \ln(a))}{\tau}\right] \quad (4)$$

The confidence bounds of POD(a) were evaluated by bootstrap method [4].

3. Results

Fig. 3 shows the linear regression between the logarithmic transformations of signal response and defect size, which was performed based on 9 observations from the original 72 observations obtained from the numerical simulations where a constant half length of flaw, Lx = 1.5 mm, and various depth of flaw from 0.1 to 9 mm are considered.

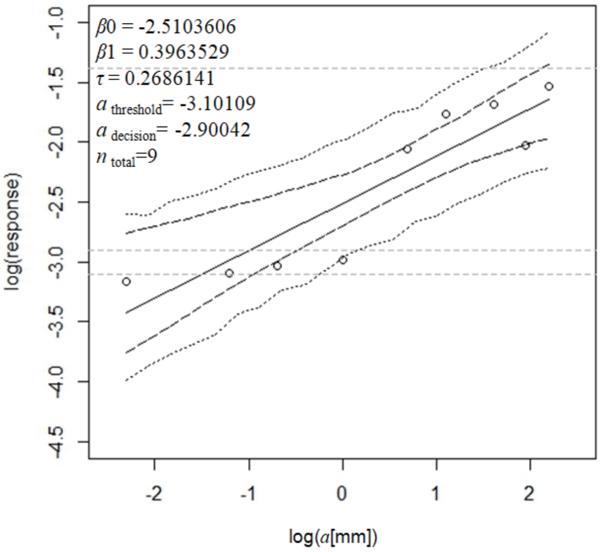

Fig. 3 Regression line with the natural logarithm of the amplitude response as a function of flaw depth with constant *Lx* = 1.5 mm (9 observations)

The solid line shows the regression line whose coefficients β_0, β_1, τ are -2.510, 0.396 and 0.269, respectively. The solid regression line is surrounded by two sets of lines, where the inner set of broken lines are the 95% regression confidence bounds and the outer set of dotted lines form the 95% prediction confidence bounds. A new In(â) value is expected to be contained by these bounds in 95 of 100 similar situations.

The result of POD for the above data is presented in Fig. 4. The solid line represents the POD curve and the broken lines are the 95% confidence bounds. The $a_{90/95}$, 1.3148 mm, intersection between 90% POD and lower 95% confidence bound, indicates that the depth of which a flaw can be detected with 90% probability and 95% confidence, which reveals that, the flaw with a depth of 1.3148 mm or larger in the weld is able to be reliably detected by the ultrasonic testing.

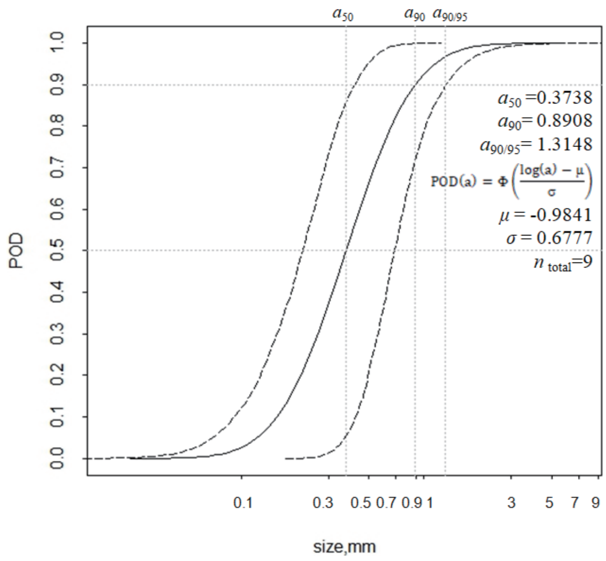

Fig. 4 POD curve for 9 observations – log x – axis(with constant *Lx*= 1.5 mm)

Another set of results was calculated in contrast with Fig. 3 &4 using other 9 points (different *Lx* and *Lz*, its sizes are shown in Table 2) sampled randomly from original 72 observations.

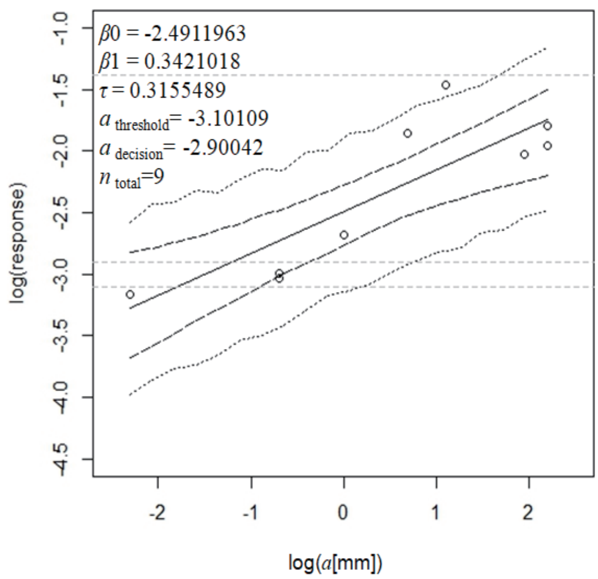

Fig. 5 Regression line in natural logarithm of the amplitude response as a function of flaw depth with different *Lx*

Figure 5 presents its linear regression with coefficients β_0 = -2.4912, β_1 = 0.342, τ = 0.315 and corresponding 95% confidence bounds. The results of POD analysis for this set of data and its 95% confidence bounds are then calculated displaying in Figure 6. The $a_{90/95}$ is equal to 1.2413 mm here.

This two sets of results indicate that there exists small changes after adding the factor of different Lx : the 95% confidence bounds of linear model gets narrower, the $a_{90/95}$ has

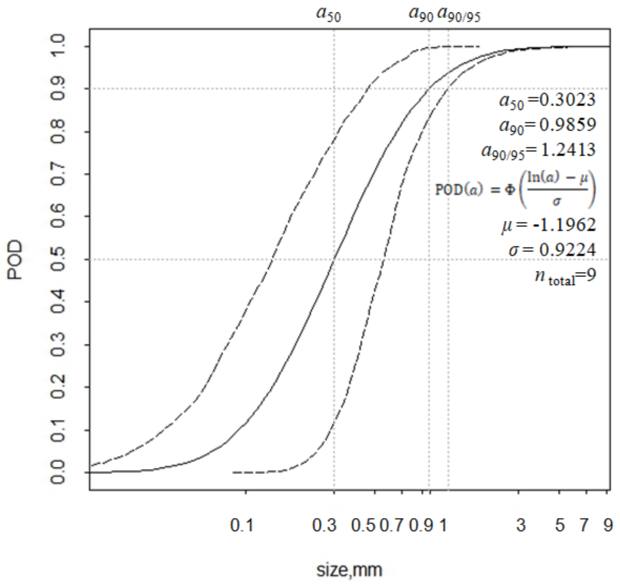

Fig. 6 POD function of flaw depth (different *Lx*, 0.5 - 4.5 mm)

slightly reduction, and the 95% confidence lines of POD curve becomes wider. While the second set of results are considering different Lx, with larger and smaller sizes than Lx = 1.5 mm. Therefore, it's reasonable to doubt that Lx may have serious affects for the consequence.

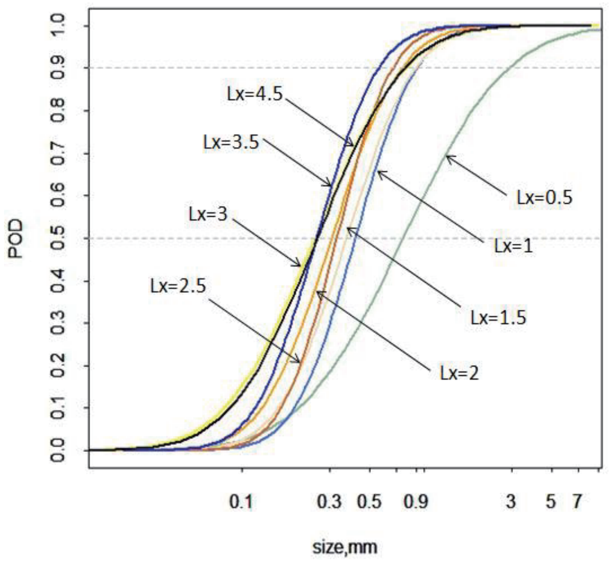

Fig. 7 POD curves of 8 sizes of *Lx* (from 0.5 to 4.5 mm)

In order to verify above idea further, POD correspond to 8 Lx sizes were calculated as shown in Fig. 7. As *Lx* gets bigger, there is a decreasing trend of a_{50} and a_{90}, which means a higher probability of detecting the defects. Hence, it can be concluded that *Lx* is one effective influence factor for POD analysis indeed.

4. Conclusion

This study evaluated the POD of ultrasonic NDT for modeled austenitic stainless-steel welds from the viewpoint of ultrasound testing.

There is no doubt that the possibility of defects being detected shows an increasing trend with the increase of detect size. The results obtained in this study indicates that the depth and length of the crack affect the outcome at the same time, more simulations need to be conducted for gaining adequate data to provide the analysis. Considering not only the depth of flaw but also the length of flaw while analyzing POD. Future work will include POD analysis using the model developed of more than one parameter characterizing the flaw size to discuss the reliability of ultrasonic NDT.

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