Investigation on electromagnetic characteristics of modeling thermal fatigue cracks in numerical simulation by eddy current testing

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The present study discusses electromagnetic characteristics of modeling thermal fatigue crack in numerical simulation from view point of eddy current testing. Two thermal fatigue cracks introduced into SUS304 stainless steel plates are investigated. Eddy current signals are gathered by a differential plus point probe with several frequencies, 50 kHz, 100 kHz and 400 kHz. In the numerical simulation thermal fatigue crack is modeled as a region with constant width, true profile revealed by results of destructive testing, and uniform conductivity firstly. Further simulations are carried out to consider the possibility of variation of electromagnetic characteristics around the edge of crack. The results show that thermal fatigue cracks should be modeled as an almost nonconductive region no matter how the frequency is utilized.

Keywords: eddy current testing; thermal fatigue crack; electromagnetic characteristics; numerical modeling; finite element method

1 Introduction

Thermal fatigue crack (TFC), as one of degradation mechanisms of nuclear power plant, is caused by, for example, periodic temperature changes. They frequently appear on several general components, e.g. T-joint where has mixture of hot and cold fluids. Therefore it is necessary to carry out non-destructive (NDT) inspection of TFC for the safety of nuclear power plant.

Recently advanced manufacturing technology of artificial TFC has enabled great convenience and reliability of NDT inspection [1]. Ultrasonic testing has been utilized for the inspection of TFC for a long time. However because of complexity of cracks, e.g. crack opening, fracture surface roughness, the performance of ultrasonic testing is affected to a certain extent. Furthermore there are few reports about inspection of TFC by other methods. Above these two points, it would be preferable to study other non-destructive method for the inspection of TFC.

Eddy current testing has a widely application for inspecting degradation of nuclear power plant. Quite a few researches about eddy current testing of cracks, e.g. stress corrosion crack (SCC), have been successfully reported [2, 3]. With the help of developed computational technology, the electromagnetic characteristics of modeling SCC have been studied and it is meaningful for evaluation of SCC by eddy current testing [4, 5, 6, 7]. Those studies indicated that it would be a nice choice for investigating electromagnetic characteristics of modeling TFC by eddy current testing.

On the bases of this background, we studied the electromagnetic characteristics of modeling TFC from view point of eddy current testing. Basic information of investigated TFCs are provided by a research project which presents non-destructive testing results of cracks as benchmark data and is regarded as an excellent communicating stage for researchers in this

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field [7].

2 Material and method

2.1 Specimen

Two thermal fatigue cracks respectively located at two SUS304 stainless steel plates were studied. These two specimens both have a length of 250 mm, a width of 150 mm and a thickness of 25 mm. To introduce TFC, thermal fatigue loading was applied with high frequency induction heating and water cooling. The growth of TFC can be controlled by careful selection of loading parameters. The artificial TFCs are similar to the real TFC.

2.2 Eddy current testing

Eddy current testing was carried out by instrument of aect-2000N. Signals were gathered with different frequencies (50 kHz, 100 kHz and 400 kHz) for these thermal fatigue cracks. Plus point probe, a kind of differential probe, was utilized and the lift-off was 1.2 mm. all of data were calibrated by signals generated from an artificial rectangular slit with a length of 20 mm, a width of 0.5 mm and a depth of 5 mm so that the maximum signal due to the slit have an amplitude of 10 V and a phase of 45 degree.

2.3 Destructive testing

Destructive testing was adopted to review the true profile of thermal fatigue crack after eddy current testing. Table 1 shows the results of destructive testing.

Table 1 Results of destructive testing

Flaw ID	length	depth
TFC 1	9.7 mm	3.5 mm
TFC 2	11.7 mm	4.1 mm

2.4 Numerical simulation

Thermal fatigue cracks were modeled as a region with constant width, uniform conductivity and true profile. The width was set to be either 0.01 mm, 0.02 mm, 0.05 mm, 0.10 mm, 0.20 mm, 0.50 mm or 1.00 mm. The conductivity of crack was assumed to be either 0.0%, 0.1%, 0.2%, 0.5%, 1.0%, 2.0%, 5.0%, or 10.0% of conductivity of base material in order to avoid too many numerical simulations. By these simulations an appropriate width and a conductivity can be defined which minimize the difference between simulated signals and experimental signals. The difference is defined by equation 1, Z_{simu} means signal of simulation and Z_{expe} means signal of experiment. Here differences between simulated signal and experimental signal at 5 positions during a scanning were summed for considering the trajectory of eddy current signal.

$$\varepsilon = \sum_{i=1}^{i=5} \left| Z_{simu}^{i} - Z_{expe}^{i} \right| \qquad (1)$$

Fig. 1 shows geometry of model of simulations. The length and width of plate is sufficient long to avoid edge effect and the depth of plate is same with that of experiments. Thermal fatigue crack was simulated with true profile. The AC/DC module of commercial software Comsol multiphysics 4.2a was utilized to carry out simulations. The governing equation is

$$(j\omega\sigma - \omega^2\varepsilon)A + \nabla \times (\mu^{-1}\nabla \times A) = J_e \qquad (2)$$

where ω is the angular frequency, σ is the conductivity, ε is the permittivity, A is the magnetic vector potential, μ is the permeability and Je is the current density of exciter. Curl element was utilized in numerical model. The size of computational domain was 200 mm × 200 mm × 200 mm. Boundary condition was imposed so that the tangential component of magnetic vector potential is zero. The total number of elements of the model was about 200,000 The mesh is sufficient fine so that error caused by mesh is only 0.08% of signal. Other size and material parameters are listed in the table 2.

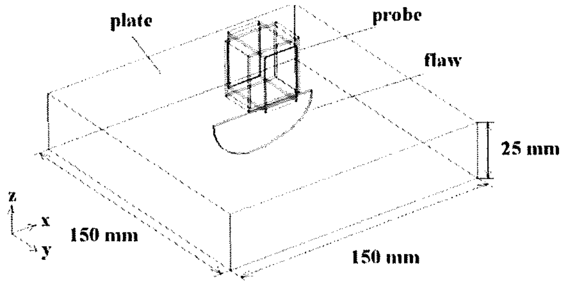

Fig.1 Geometric model of simulation

Table 2 Size and material parameters

Item	Value
Conductivity of plate	1.35×10^{6} S/m
Relative permeability of plate	1.0
Width of probe	3.0 mm
Length of probe	5.0 mm
Height of probe	5.0 mm
Thickness of probe	0.2 mm
Current density of exciter	1.0×10^{6} A/m^2
The number of detector coil turns	100

3 Results and discussion

Table 3 shows results of simulations. The appropriate width and conductivity are listed for each crack with different frequencies. By these results, the thermal fatigue cracks tend to have larger width and conductivity with the increase of frequency and TFC should be modeled as an almost nonconductive region no matter what the frequency is. Furthermore it is shown that when the higher frequency is employed the error between experimental signal and simulated signal becomes smaller. It can be explained by the fact that eddy current signals of simulation are less affected by the error of defining profile of thermal fatigue cracks because skin depth becomes shallower when higher frequency is utilized.

Table 3 Appropriate width and conductivity of modeling of TFC

Flaw ID	Frequency (kHz)	Width (mm)	Conductivity (%)	Error, ε (V) *
TFC 1	50	0.01	0.0	1.7466
	100	0.10	0.1	1.4809
	400	0.10	0.1	1.1363
TFC 2	50	0.01	0.0	2.7922
	100	0.01	0.0	1.5720
	400	0.05	0.0	1.4479

The error is defined as the equation 1.

Fig. 2, 3, 4 demonstrate the experimental and simulated signals (after calibration) during the scanning process when the probe is directly above the thermal fatigue crack. Scanning distance 0 mm means the center of TFC is under the probe. They show well agreement between experiment and simulation and that proves the correctness of the modeling of this study.

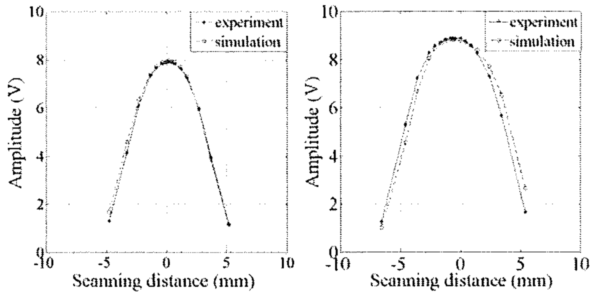

Fig.2 Experimental and simulated signal of inspecting TFCs by 50 kHz (left: TFC 1, right: TFC 2)

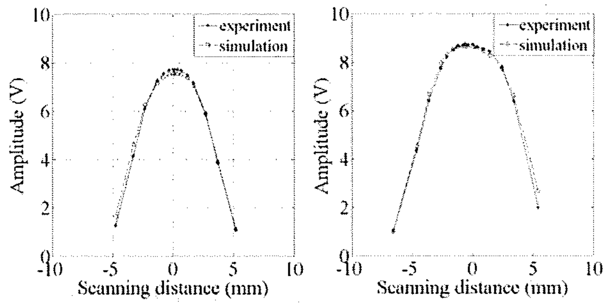

Fig.3 Experimental and simulated signal of inspecting TFCs by 100 kHz (left: TFC 1, right: TFC 2)

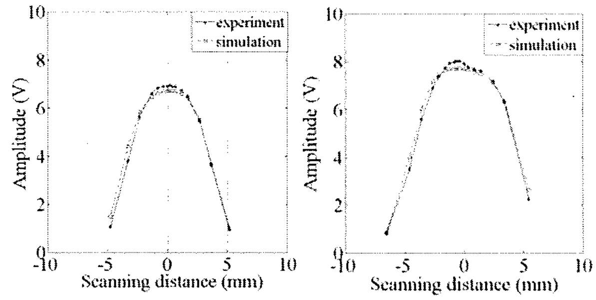

Fig.4 Experimental and simulated signal of inspecting TFCs by 400 kHz (left: TFC 1, right: TFC 2)

Furthermore, simulations were carried out to consider the variation of electromagnetic characteristics around edge of TFC which would be caused by the plastic deformation of crack or generation of oxide layers during the production of TFC. Fig. 5 shows the Lissajou's pattern of inspecting TFC 1 by considering conductive edge when 50 kHz is utilized. The result indicates that it is not necessary to consider the conductivity of edge of TFC because signals of simulation would rotate anticlockwise with the