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Eddy Current Testing System for Heat Affected Zone of In-Core Monitor Housing Inner Surface

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ABSTRACT

We verified that eddy current testing (ECT) has enough detectability for a welded part position of in-core monitor (ICM) housing outside and defects on a heat affected zone (HAZ) in welding of the inner surfaces for a special inspection involved in long-term operation. It is difficult to determine an appropriate inspection area if an actual welded position of an ICM housing is different from a designed position. It is presumed that detectability of ECT is decreased because a HAZ of an ICM housing inner surface is deformed by welding. We conducted a full-scale mock-up test using a simulated ICM housing specimen with a welded part and an ECT system which consisted of a welded part detection probe, a rotational ECT probe and probe moving equipment and confirmed that the ECT detected a welded part position of outside and defects of about 0.5 mm in depth despite existences of inner surface deformations of approximately 1 mm.

KEYWORDS

Non-destructive inspection, Eddy current testing, Heat affected zone, In-core monitor housing, Nuclear reactor, Special inspection, Long-term operation

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1. Introduction

Eddy current testing (ECT) was required for a stress corrosion cracking (SCC) on a heat affected zone (HAZ) in welding part of an in-core monitor (ICM) housing inner surface, which locates in a boiling water reactor, as one of the special inspection items for Japanese nuclear power plants of long-term operation over 40 years by Japanese nuclear regulation authority in 2013 [1]. An ICM housing is fixed to a bottom of a reactor pressure vessel (RPV) by welding [2]. It is difficult to determine an appropriate inspection area from an inside of an ICM housing if an actual welded position of an ICM housing is different from a designed position. It is presumed that a HAZ of an ICM housing inner surface is deformed by welding. A deformation of an inspected surface generally decreases detectability of ECT to defects on the surface [3, 4]. In an inspection inside a tube, there are many reports regarding influences of a support plate and an expansion transition area on a tube outer surface [5]. In this development, we featured a deformation of a tube inner surface.

We conducted a full-scale mock-up test using simulated ICM housing specimens with a welded part and an ECT system which consisted of a welded part detection probe, a rotational ECT probe and probe moving equipment in order to verify detectability of both a welded part position and defects. In this paper, we describe results of the full-scale mock-up test and a discussion of its validity.

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2. Experimental Equipment

2.1. Welded specimens

We prepared welded specimens S1-S3 which have the same shape and different defects one another. A schematic of the welded specimen S1 which simulates a welded part of an ICM housing is shown in Fig. 1 [6]. The simulated ICM housing is nearly 50 mm in outer diameter, 40 mm in inner diameter and 130 mm in length [2]. The welded specimen S1 has the part welded to a simulated cladding in the same way as an actual plant to reproduce a deformation of a real inspected surface at the center, and a flange at each end to be extended by a full-scale length. SUS316 was selected as the simulated cladding material because it is close to an actual material (nickel alloy) in electrical conductivity which influences detectability [4], and easily obtained. The welded specimen S1 was given electrical discharge machining (EDM) slits as simulated defects of about 10 mm in length, 0.5 mm in depth, 0.25 mm in width and longitudinal directions of 0° and 22.5° which are angles to a housing axis on a HAZ of circumferentially opposed inner surfaces. The HAZ has contracted and expanded deformations of about 1 mm in radial direction as in Fig. 2. Specifications of the EDM slits on the welded specimens S1-S3 are shown in Table 1.

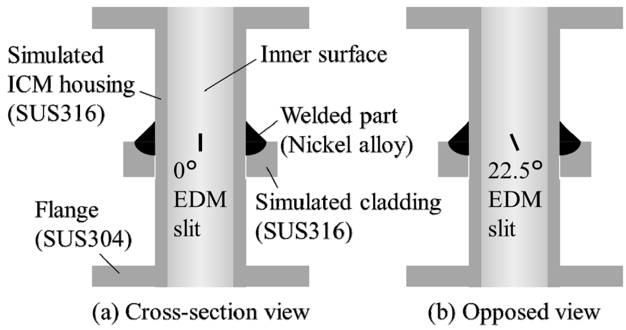

Fig. 1. Schematic of welded specimen S1

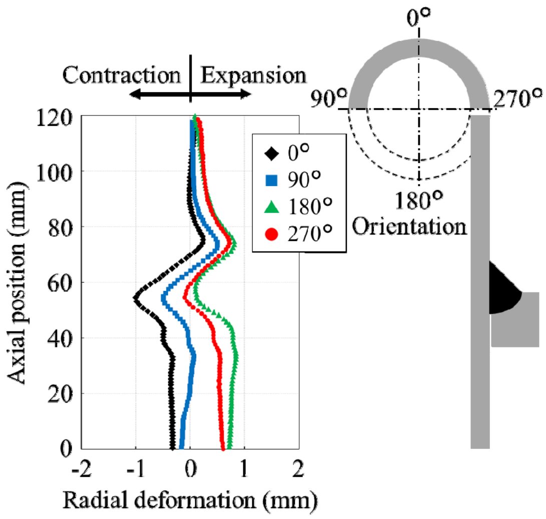

Fig. 2. Measured deformation amounts of welded specimen S1

Table 1 Specifications of EDM slits

Specimen No.	Simulated defects (EDM slits)				
	Direction (°)	Cross-sectional shape	Length (mm)	Depth (mm)	Width (mm)
S1	0	Circular arc	Approx. 10	Approx. 0.5	Approx. 0.25
	22.5				
S2	45				
S3	90				

2.2. Probes and moving equipment

We used two kinds of probes. One is a welded part detection probe, and the other is a rotational ECT probe for detecting defects. The welded part detection probe has two same shape bobbin coils [3] to detect a welded part position of an ICM housing outside. The rotational ECT probe [3, 6, 7] consists of two same shape cross coils [4] whose directions to an inspected surface are different by 45° to detect defects of all longitudinal directions because sensitivity of a cross coil to a defect depends on a relative positional relationship between the cross coil and the longitudinal direction of the defect. The cross coil is inscribed in a circle which has a diameter of 4 mm. We defined the cross coils which have the highest sensitivity to the 0° (or 90°) and the 45° EDM slits as the 0° and the 45° coils, respectively. The two cross coils which were set at circumferentially opposed positions on the rotational ECT probe are pushed toward the deformed inner surfaces of the specimens by springs to keep a constant lift-off.

It is possible to access a HAZ of an ICM housing inner surface from both an inside of an RPV and a pedestal side. Probe moving equipment shown in Fig. 3 was prepared for the latter case in this test [6]. Right and left flange connections marked with an asterisk * in Fig. 3 are the same parts, which means that the right figure is located in the upper part of the left one. The probes are passed into a calibration specimen [4] attached to a flange of an extension ICM housing and moved in axial direction of the extension ICM housing and the welded specimen by an elevating stage connected to the probes with a pole by plungers. Some poles are added to this equipment depending on a height between the lower flange of the extension ICM housing and the welded part of the welded specimen. A rotating speed of the rotational ECT probe and a moving velocity of the elevating stage were appropriately adjusted to detect defects well.

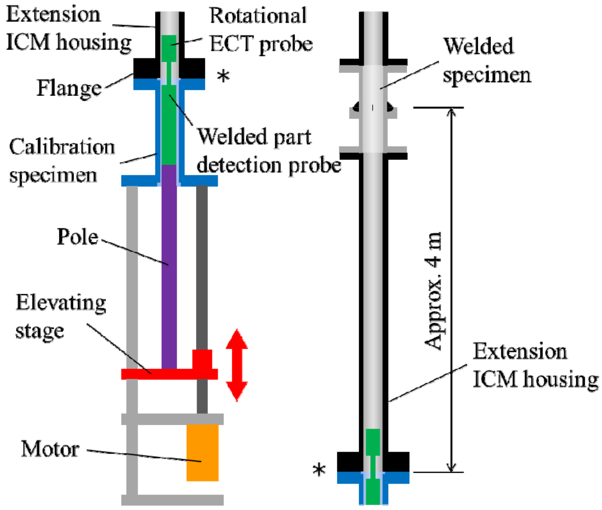

Fig. 3. Schematic of probe moving equipment

3. Experimental Procedures

We conducted a full-scale mock-up test at the welded part of the welded specimen which is approximately 4 m above the lower flange of the extension ICM housing (Fig. 3). A frequency of the bobbin coils operated in self-induction type self-comparison arrangement or differential mode [3, 4] for the welded part detection was 50 kHz. An axial scanning length of the welded part detection probe was 100 mm including the welded part. The cross coils on the rotational ECT probe were also operated in the differential mode at the frequency of 500 kHz and moved 45 mm in the axial direction over the whole circumference on the HAZ in the vicinity of the welded part after a reference sensitivity and a phase angle were set using the calibration specimen given a reference defect based on a Japanese ECT guideline [4]. Experimental conditions are shown in Table 2.

Table 2 Experimental conditions

Welded part detection test	
Coil	Bobbin coils
Operational Mode	Self-induction type self-comparison arrangement (differential)
Frequency	50 kHz
Scan area	Axial: 100 mm
Defect detection test	
Coil	Cross coils
Operational Mode	Self-induction type self-comparison arrangement (differential)
Frequency	500 kHz
Calibration specimen	Material: SUS316, Inner diameter: Approx. 40 mm Simulated defects: EDM slits of 80 mm in Length, 1 mm in depth, 0.3 mm in width, 0° and 45° in direction
Scan area	Axial: 45 mm, Circumferential: 360°

4. Experimental Results

4.1. Welded part detection test

A result of a welded part detection test and a measured diametrical deformation amount using the welded specimen S1 are shown in Fig. 4. An output signal of the welded part detection probe indicated the maximum at the upper end position and the minimum at the lower end position of the welded part. The signal may be influenced by the deformation of the inner surface because an axial coil position of the maximum or the minimum signal from the bobbin coils operated in the differential mode nearly coincides with that of the largest positive or negative slope of the diametrical deformation. Therefore, we confirmed that the bobbin coils were able to detect the welded part position of the ICM housing outside at least indirectly.

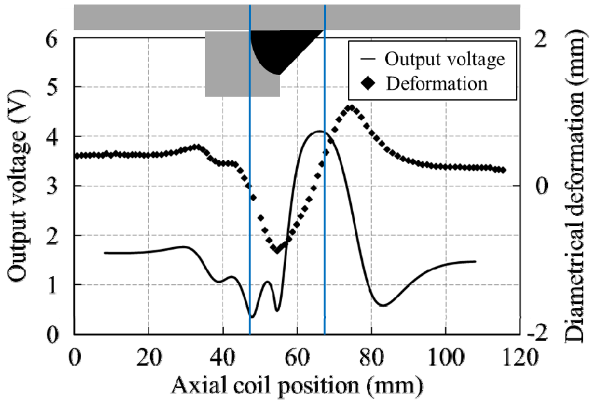

Fig. 4. Result of welded part detection test using welded specimen S1

4.2. Defect detection test

A result of a defect detection test (welded specimen S1, 0° coil) and measured sensitivities to all the EDM slits are shown in Fig. 5 and Fig. 6. A C-scope image shown in Fig. 5 represented clear signals from the two EDM slits on the welded specimen S1. According to Fig. 6, the cross coils detected the EDM slits of all directions in more than 20% (0° slit by 0° coil: 63%, 45° slit by 45° coil: 49%, 90° slit by 0° coil: 44%) of the reference sensitivity which the Japanese ECT guideline recommended as a general criterion for extracting a signal from a defect [4]. We verified that the cross coils were able to detect the defects of about 10 mm in length and 0.5 mm in depth despite the existence of the inner surface deformations of approximately 1 mm. We also confirmed that a sensitivity to the 22.5° slit decreased by 33% in the 0° coil, 41% in the 45° coil from each maximum value. There was a variation of 32% in the sensitivities to the 22.5° slit between the 0° and the 45° coils.

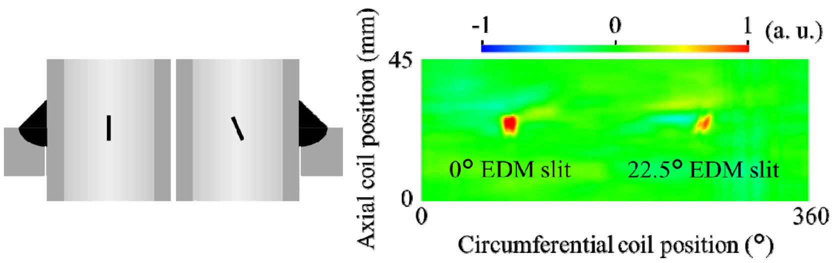

Fig. 5. Result of defect detection test using welded specimen S1 and 0° coil

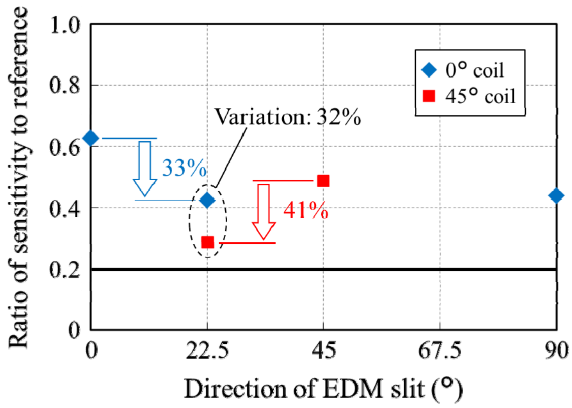

Fig. 6. Measured sensitivities to all EDM slits

5. Discussion

Sensitivities to the 0° slit by the 0° coil, the 45° slit by the 45° coil and the 90° slit by the 0° coil should be the same values essentially. However, they indicated the different values in the defect detection test. Furthermore, the variation in the sensitivities to the 22.5° slit between the 0° and the 45° coils was observed. We verified and discussed the validity of the results of the full-scale mock-up test by comparison with those of a fundamental test using a planar specimen. Sizes of EDM slits on the planar specimen and a planer calibration specimen were the same as those of the specimens in the full-scale mock-up test.

A relationship between the measured diametrical deformation amounts of the welded specimens S1-S3 and positions of the EDM slits (0°, 45° and 90° slits) on these specimens in the full-scale mock-up test is shown Fig. 7. The 0° slit and the 90° slit were given on the most and the least contracted inner surfaces respectively. An experimental result of a relationship between sensitivity and lift-off (a gap length between an ECT probe and a surface of a specimen) in the test using the planar specimen and the 0° coil is shown in Fig. 8. The sensitivities of approximately 40% to 60% to the 0°, the 45° and the 90° slits in the full-scale mock-up test correspond to the lift-off values of approximately 0.1 mm to 0.3 mm. From Figs. 7 and 8, we considered that the sensitivities to the 0° slit by the 0° coil, the 45° slit by the 45° coil and the 90° slit by the 0° coil indicated the different values in the full-scale mock-up test because the lift-off values became variously shorter than a design value of 0.3 mm by the contractions of the welded specimen inner surfaces. For this reason, the measured sensitivities in the full-scale mock-up test are roughly valid.

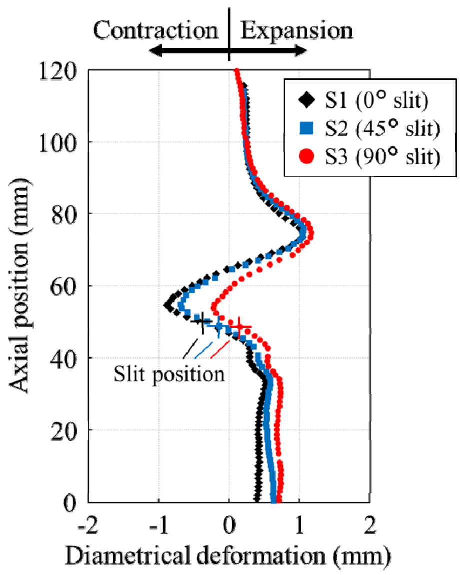

Fig. 7. Relationship between measured diametrical deformation amounts and EDM slit positions

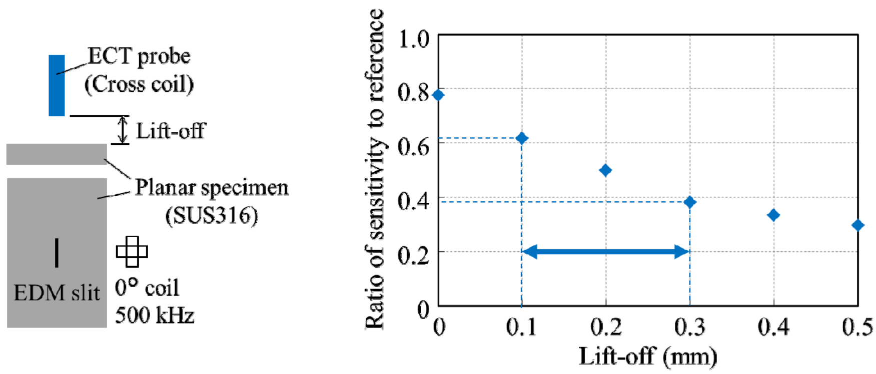

Fig. 8. Relationship between sensitivity and lift-off in test using planar specimen

An experimental result of a relationship between sensitivity and EDM slit direction in the test using the planar specimen, the 0° and the 45° coils is shown in Fig. 9. A lift-off was constant value of 0.3 mm in this test. The sensitivity to the 22.5° or the 67.5° slit decreased by 34% in the 0° coil, 33% in the 45° coil from each maximum sensitivity. There was a variation of 20% in the sensitivities to the 22.5° slit between the 0° and 45° coils although both measurements were performed with the same cross coil by tilting its orientation for each case. We considered that the variation of 20% was caused by a variation in the shape between the two tangential coils [3] that compose this cross coil. From this result, we figured the variation of 32% in the full-scale mock-up test in which the two cross coils were used as the 0° and the 45° coils on the two welded specimens S1 and S2 with the different deformations was reasonable value.

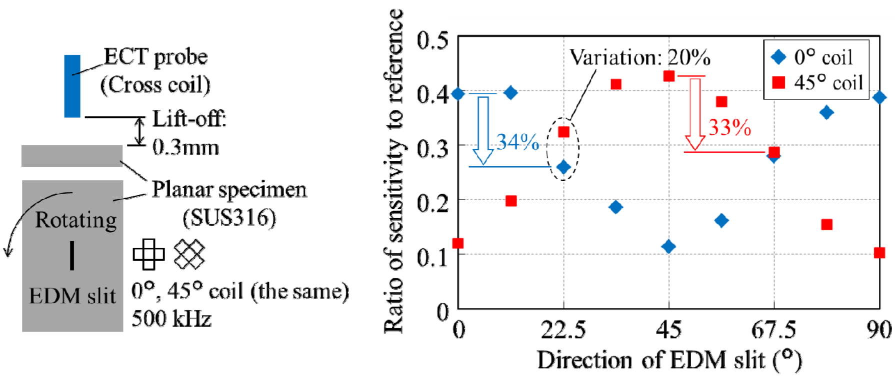

Fig. 9. Relationship between sensitivity and EDM slit direction in test using planar specimen

6. Conclusion

We performed the full-scale mock-up test using the simulated ICM housing specimens with the inner surface deformations and verified that the ECT has enough detectability for the welded part position of the ICM housing outside and the defects on the HAZ in welding of the inner surface despite the existence of the deformations. In the welded part detection test, the output signal of the ECT indicated the maximum at the upper end and the minimum at the lower end of the welded part. In the defect detection test, the ECT detected the EDM slits of 10 mm in length and 0.5 mm in depth in more than 20% of the reference sensitivity. The results of the full-scale mock-up defect detection test were valid according to the comparison with the fundamental test using the planar specimen. We are going to confirm detectability to an SCC as a future work.

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