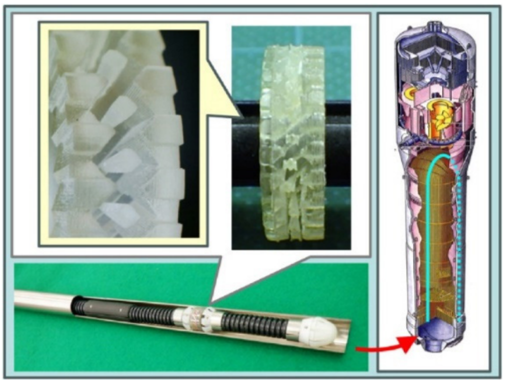
Approach to Fabrication of Insertion Type Cross Coil Array ECT Probe Using Additive Manufacturing Technology



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As existing PWRs have been restarted and their operation periods extended in order to achieve both decarbonization of power sources and stable power supply, efforts to realize innovative light water reactors, and the development of fast reactors and high-temperature gas-cooled reactors, have progressed. For long-term maintenance of nuclear power plants, establishing eddy current test inspection technology for steam generator heat-transfer tubes of various specifications is needed. Consequently, a prototype of an insertion type cross coil array eddy current test probe with high customizability has been developed using the additive manufacturing method, which can fabricate parts with structures and shapes that cannot be created by conventional machining techniques, and verified. As a result, the possibility of providing probe with heat-transfer tubes of various specifications, while maintaining the same performance and quality as conventional probe, was obtained.

1. Introduction

Nuclear power generation does not emit CO_2 during operations nor is it easily affected by weather conditions. For this reason, the Agency for Natural Resources and Energy promotes the use of nuclear power while placing the highest priority on safety, in order to achieve both decarbonization of power sources and stable power supply [(1)]. From such background, the restart/operation period extension of the existing Pressurized Water Reactor (PWR) advances, and the realization of the advanced light water reactor incorporating further safety measures is tackled. And, the development of fast breeder reactor and high-temperature gas-cooled reactor is also started for the future effective utilization of nuclear energy. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) promotes upgrading of maintenance technology in order to realize long-term safe operation of these nuclear plants.

In current PWRs, two to four steam generators (hereinafter referred to as SGs) are installed per plant as the main components, and contain approximately 3,400 heat-transfer tubes made of nickel-based alloy and a total length, outer diameter and wall thickness of approximately 20 m, 20 mm and 1.3 mm, respectively. During the regular inspection of SGs, one item of the main inspection methods is eddy current testing (hereinafter referred to as ECT) of the heat exchanger tubes. Application of ECT to heat exchanger tubes of SGs in advanced light water reactors, fast breeder reactors, and high-temperature gas-cooled reactors is expected, but the heat-transfer tubes to be used are assumed to vary in outer diameter, wall thickness, and material specifications depending on the type of furnace. From now, establishing ECT inspection technologies suitable for various heat-transfer tube specifications when performing maintenance work is needed, hence a probe which can easily switch between different specifications is desirable. Consequently, based on technology established for intelligent ECT probe (hereinafter referred to as “conventional probe”),

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which have an high defect detection/defect direction characterization performance, can carry out high-speed inspection, and have been proven in the inspection of SG heat-transfer tubes in existing PWRs, MHI has begun development of a new type of insertion type cross coil array ETC probe (hereinafter referred to as “new probe”) that can be used for heat-transfer tubes with various specifications.

More than 20 years have passed since the development of conventional probe. Meanwhile, additive manufacturing (hereinafter referred to as AM) technology has advanced and is now capable of fabricating parts with structures/shapes that could not be realized by conventional machining or injection molding [(2)]. Therefore, to improve manufacturability and to ensure the manufacturing ability of probes and high customizability for heat transfer tubes of different specifications, a coil structure that utilizes AM technology in the fabrication of probe components was devised. Specifically, cross coils consisting of two orthogonal coils, one large and one small, are inserted into the grooves on a coil holder fabricated by AM technology and arranged in an array in the circumferential direction of the probe.

In addition, conventional probe use resin parts in multiple locations other than the coil holder, and these parts are manufactured by injection molding. However, customization of these injection-molded parts suitable with heat-transfer tubes with different specifications is difficult and requires the fabrication of new molds each time. Therefore, to eliminate the need to fabricate/update molds when there is a change in specifications, application of AM technology in the fabrication of resin parts other than the coil holders was considered, and an applicable AM method was selected.

This paper presents the results of these efforts and reports the results of tests conducted to confirm detectability of the new probe on electrical discharge machining (hereinafter referred to as EDM) slits made on the inner/outer surfaces of the heat-transfer tubes in the circumferential/axial direction as artificial defects.

2. Overview of cross coil array probe

Conventional probe currently used for SG heat-transfer tube inspection is mutual induction array probe that can detect defects with a high S/N ratio* and can also discriminate the direction of the defects [(3)] **Figure 1** shows an overview of the SG heat-transfer tubes to be inspected and the thin-film coil used as the detection coil in conventional probe.

* For the S/N ratio, S (Signal) is the defect signal and N (Noise) is the noise signal. The higher the S/N ratio, the better the discrimination performance of the defective signal.

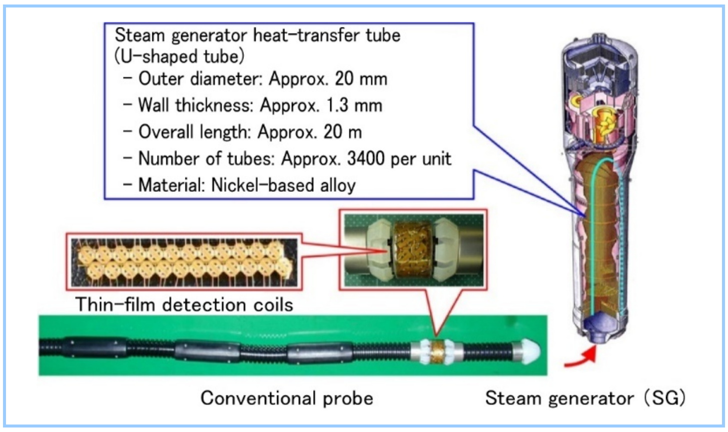

Figure 1 Conventional probe and thin-film detection coil

Etching the metal laminate film, which is part of the thin-film detection coil manufacturing process, requires high technical ability, and changes in design require verification of the feasibility of manufacturing each time. As a result, customization associated with changes in heat-transfer tube specifications requires considerable effort. In addition, to generate eddy currents that meet the design specifications, the positional relationship between the thin-film detection coil and the excitation coil must be precisely controlled during probe assembly, requiring highly skilled workers to assemble the probes.

To address these issues, a cross coil that combines two types of simple coils of different sizes (one large, one small) in an orthogonal configuration, which can be fabricated by automatic winding, was devised. **Figure 2** shows a conceptual diagram of the cross coil. The cross coil consists of an excitation coil on the outer side and a detection coil with a smaller dimension inserted inside the excitation coil. The cross coil operates by mutual induction the same as conventional probe [4]. The cross coils can be placed next to each other at narrow intervals and used as an array probe with high circumferential resolution. In order to improve the defect detectability by increasing the number of coil turns while preventing physical interference between adjacent coils, the excitation coil is rectangular and the detection coil is trapezoidal as shown in **Figure 3**. This structure allows the probe specifications to be flexibly changed according to the heat-transfer tube specifications while maintaining a high S/N ratio.

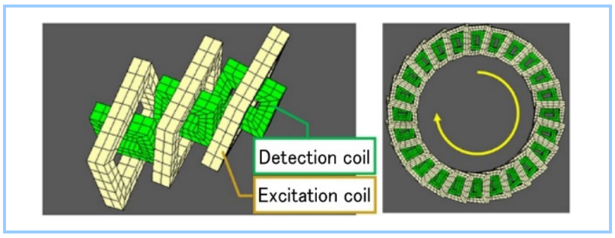

Figure 2 Conceptual diagram of cross coil and circumferential array arrangement

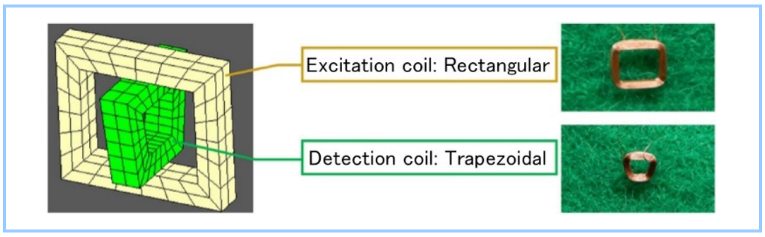

Figure 3 Cross coil combining rectangular excitation coil and trapezoidal detection coil

3. Efforts to fabricate new probe using AM technology

3.1 Application of AM technology to coil holder

For the assembly of cross coil array probe, a coil holder was designed to hold the excitation/detection coils as shown in **Figure 4**. To assemble an array probe, a method to precisely combine the small-size excitation/detection coils and arrange them in the circumferential direction of the probe must be established. Therefore, the coil holder has grooves that match the dimensions and positional relationship of the excitation/detection coils in order to easily achieve assembly work by simply inserting the cross coils into the corresponding grooves.

On the other hand, the designed coil holder structure could not be fabricated using conventional machining or injection molding due to its complex shape and difficulty ensuring the required high dimensional accuracy to attach the coils at the desired positions. For this reason, stereolithography, an AM method, was used. **Figure 5** shows the completed coil holder.

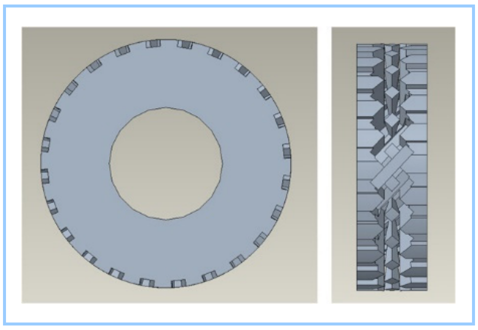

Figure 4 3D drawing of coil holder

Figure 5 Coil holder fabricated using AM technology

The head of the new probe assembled by inserting cross coils into the grooves of a coil holder is shown in **Figure 6**. A conventional probe has a total of 24 coils (12 coils x 2 columns) arranged in the circumferential direction. The new probe, however, achieves the same circumferential resolution as the conventional probe with 24 coils x 1 column. As a result, a margin in the axial length of the head can be obtained, and a groove for signal lines can be provided around the coil, thus facilitating the assembly of the probe and providing a design margin for ensuring stable manufacturing quality.

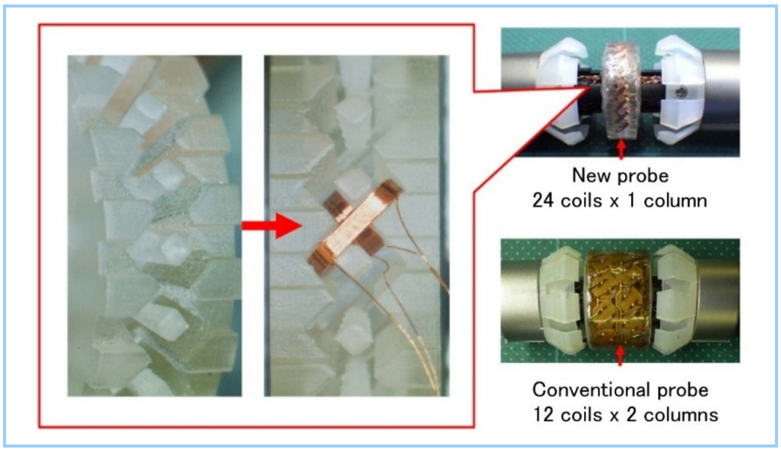

Figure 6 Head of new probe assembled by inserting cross coils into the grooves of coil holder and head of conventional probe

3.2 Application of AM technology to devices other than the coil holder

Seeking to apply AM technology to resin parts other than the coil holder, prototypes of two parts were fabricated as shown in **Figure 7**. The part in Figure 7(a) is difficult to fabricate because wall thickness is thin in some places, and material chemical composition is limited so as not to affect the integrity of plant equipment since it is in direct contact with the inner surface of the heat-transfer tube. The part in Figure 7(b) is also difficult to fabricate due to its complex shape.

In order to determine the AM method to apply, four AM methods, stereolithography, selective laser sintering, material jetting, and fused deposition modeling were selected and evaluated from three standpoints; molding accuracy, strength, and material chemical composition. As a result of the prototype evaluation, parts fabricated by the fused deposition modeling method were found to satisfy each evaluation item. Parts fabricated by the fused deposition modeling are shown in **Figure 8**. Compared to the injection-molded parts shown in Figure 7, no significant difference in appearance was observed and the quality required for application in actual equipment could be confirmed.

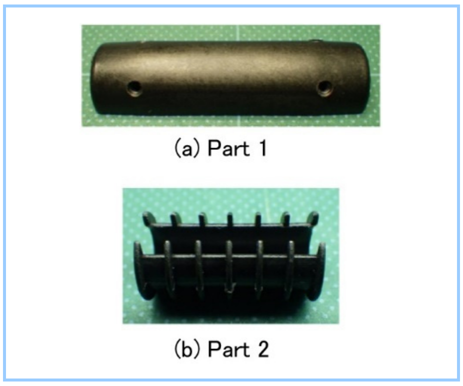

Figure 7 Resin parts fabricated by injection molding

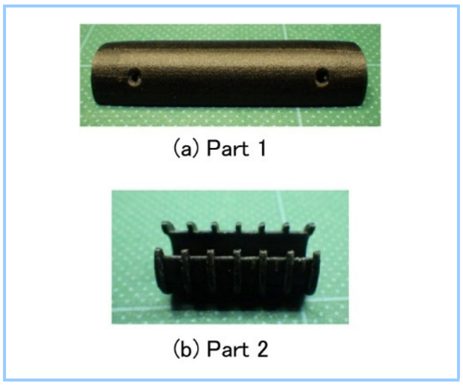

Figure 8 Resin parts fabricated by fused deposition modeling

4. Evaluation of new probe prototype

The external appearance of the fabricated prototype of the new probe is shown in **Figure 9**. Using this probe, testing to confirm defect detection performance was conducted using a heat-transfer tube with circumferential/axial EDM slits at a depth of 20%t (t: tube thickness of about 1.3 mm) on the inner/outer surface of the tube which were applied as artificial defects. As a result, the probe was able to detect all the defects.

From the results of the tests to confirm defect detection performance of (a) the new probe and (b) the conventional probe, signal waveform and color tone images which the signal amplitudes of the artificial defects, are shown in **Figure 10**. According to the signal waveforms it could be confirmed that the signal phase angle of the new probe changed according to the defect direction in the same characteristics as that of the conventional probe. The color tone image shows that the new probe has the same detection performance and S/N ratio as a conventional probe. From the above, the possibility that the new probe has the same defect detection/defect direction characterization performance as a conventional probe was obtained.

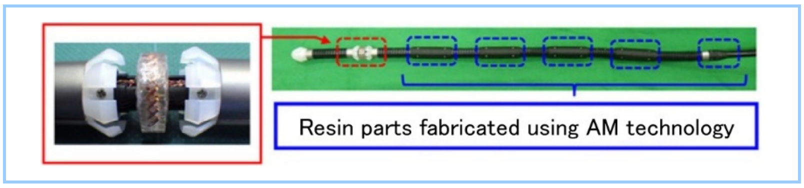

Figure 9 Prototype of the new probe

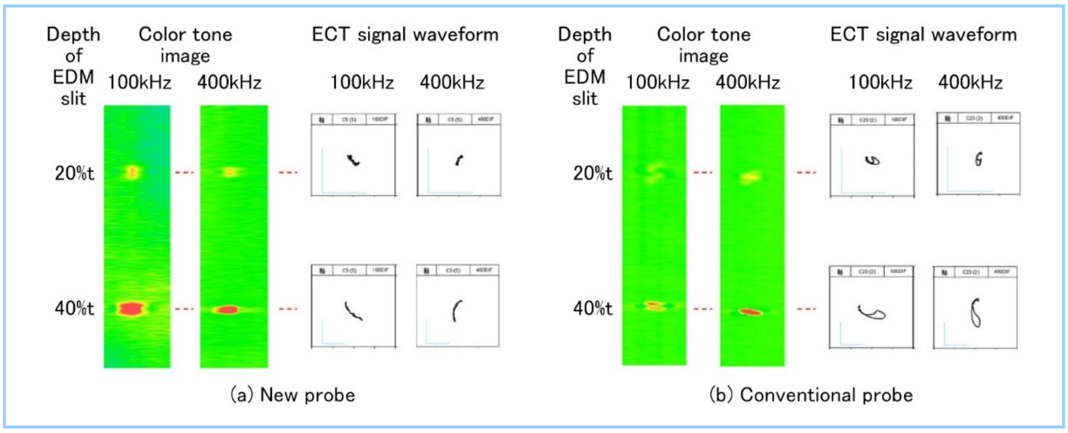

Figure 10 Results of detectability confirmation tests with new probe and conventional probe

5. Conclusion

As a result of efforts by MHI to fabricate a new probe using AM technology, the following results were obtained, and the possibility of providing array probe that can be used for heat-transfer tubes with various specifications, while maintaining the same performance/quality as conventional probe, was obtained.

(1) A new cross coil structure that combines two simple-shape coils was devised using AM technology.

(2) Prototypes of resin parts of the new probe were fabricated using several AM methods and evaluated from the standpoint of molding accuracy, strength, and material chemical composition. As a result, the parts fabricated by fused deposition modeling were found to satisfy each evaluation item, and the possibility of fabricating resin parts using AM technology was obtained.

(3) Testing to confirm defect detection performance by the new probe prototype was conducted. As a result, the new probe was able to detect circumferential/axial EDM slits with a depth of 20%t applied on the inner/outer surface of the heat-transfer tube as artificial defects with a high S/N ratio, and the possibility that the new probe would have the same defect detection/defect direction characterization performance as conventional probe was obtained.

MHI will continue to promote the development of the new probe while seeking its application in actual equipment, and will contribute to the maintenance activities of nuclear power plants.

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