Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

A Novel Approach to Foreign object Management in SG Tubes: The In-Bore EDM System

Sangbeom Nam [a], Byungki Kim [a*], Geunhwe Park [b]
[a]*School of Mechatronics Engineering, Korea University of Technology and Education, Cheonan, Korea*
[b]*Korea Nuclear power Robotics LLC., Research Institute., 32-15, Techno 7-ro, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: byungki.kim@koreatech.ac.kr*

***Keywords :** remote handling, steam generator, heat exchange tube, in-bore, electrical discharge machining

1. Introduction

The steam generator, located in the nuclear power plant, serves as a specialized heat exchanger, operating on both the primary (1st) and secondary (2nd) sides. It circulates a high-temperature and high-pressure coolant, heated by the nuclear fuel fission reactions inside the reactor. This heated coolant then interacts with a working fluid that drives a turbine generator. Positioned at the intersection between the radioactive coolant (1st side) from the reactor and the non-radioactive external system (2nd side), the steam generator is a crucial component in the nuclear power plant's framework.

The arrangement of the Steam Generator heat exchange tube (SG tube) on the primary side in the Korean Standard Nuclear Power plant (KSNP) steam generator is designed in a U-bend configuration. This configuration features two 90° bends with precise curvature, coupled with a straight section. Alloy 690, chosen for its optimal thermal efficiency, is the preferred material for these heat exchange tubes. Due to the high-temperature and high-pressure conditions maintained within these primary side heat exchange tubes, Stress Corrosion Cracking (SCC) is observed [1].

The internal architecture of the steam generator undergoes substantial variations, contingent upon its designated function, which encompass dimensions, proportions, and quantities of heat exchange tubes. As a customary configuration, these tubes assume a clustered arrangement, characterized by segments both linear and curvilinear. These components are meticulously crafted from materials including Inconel, stainless steel, copper alloys, and titanium, frequently distinguished by thicknesses spanning from 0.7 to 2.0 mm. The numerical scale of internal heat exchange tubes within the steam generator is subject to discernible fluctuations, spanning from 1,000 to 13,000, based on their intended utility. This range facilitates a multifaceted spectrum of manufacturing strategies.

Steam generator maintenance is conducted periodically, and owing to advancements in inspection technologies, there is a growing incidence of identifying extraneous materials within the steam generator structure [2]. As highlighted in a report by the World Association of Nuclear Operators (WANO), a diverse array of foreign objects, including wires, bolts, and even tools like hammers, have been detected within the internal components of steam generators. This presence of foreign materials during the manufacturing phase of the steam generator is ascribed to lapses in inspection protocols and management practices, stemming from human errors.

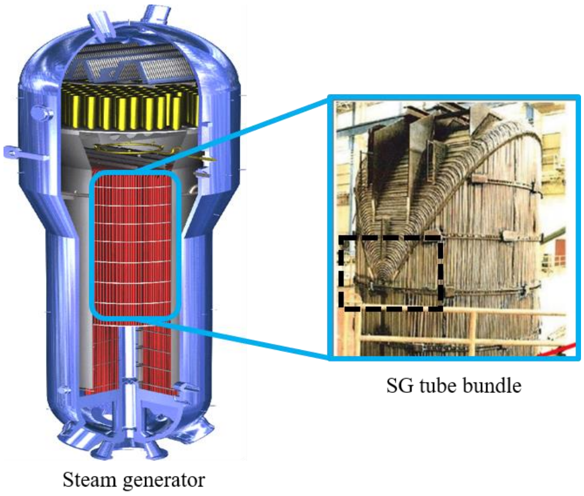

Fig. 1 Schematics of APR1400 Steam generator main device and SG tube bundle.

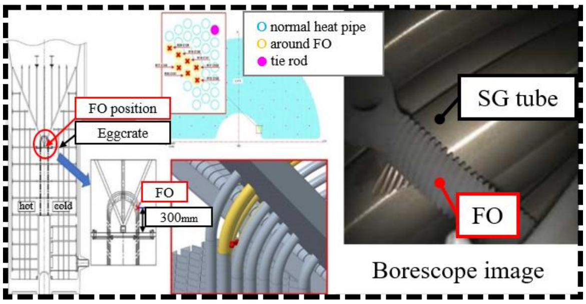

Fig. 2 Foreign Objects in SG tube Bundle.

In this study, we propose a miniature in-bore Electrical Discharge Machining (EDM) system designed for the safe removal of foreign materials located around the SG tubes within a nuclear power plant's steam generator. Targeting specific regions near the U-BEND, this system employs EDM technology to remotely and automatically create a passage window in the SG heat exchange tube for the removal of foreign objects. This is achieved without causing additional mechanical stress on the SG tube, ensuring a stable passage for the removal of foreign objects from the secondary side. Additionally, this in-bore EDM system allows for remote handling, which minimizes radiation exposure for nuclear workers.

2. In-Bore EDM tool Design

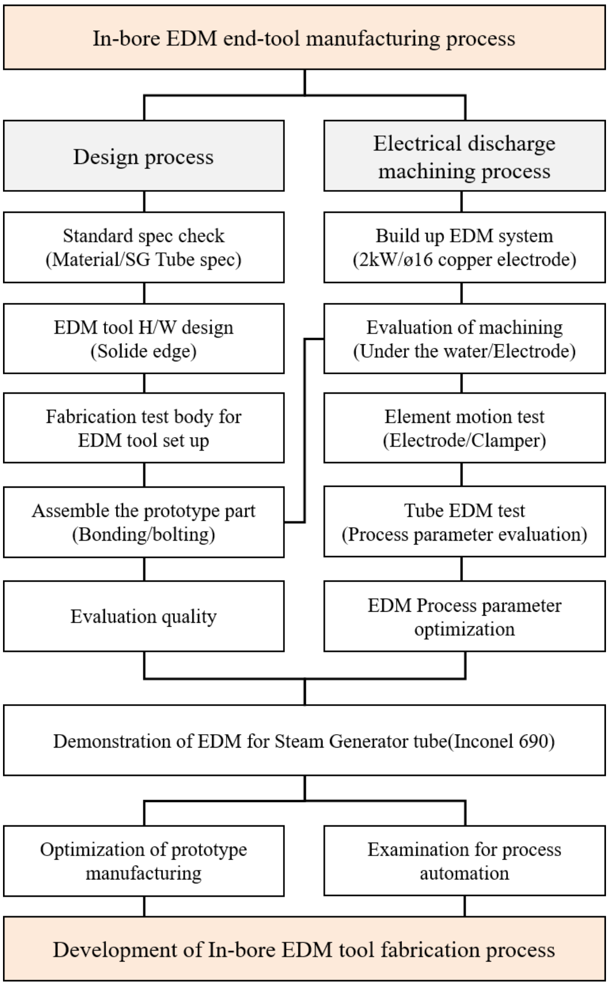

Fig. 3 Flow chart for in-bore EDM end-tool process development to remove foreign object.

To develop an in-bore EDM end-tool for SG tubes, research is essential on the miniaturization of the end device. This device should be capable of artificially inducing the discharge machining phenomenon between the workpiece and the electrode. Furthermore, technologies are needed to accurately transport this device to its designated location. Fixation methods are also critical to ensure the end device within the heat transfer tube remains unaffected by external disturbances. This includes preventing positional shifts due to tension and expansion forces when connected to the power supply cable. Fig. 3 presents a flow chart outlining the sequence of experiments executed to develop these technologies.

To develop the in-bore EDM technology for SG tubes, we prioritized research on the miniaturization of the EDM end device design and divided our focus on the EDM process control research.

Firstly, in the EDM end device design study, to ensure normal discharge machining between the workpiece and the electrode when the device is inserted using an in-bore EDM system inside the SG tube, all hardware in contact with the inner surface of the SG tube, excluding the electrode, must be insulated [3].

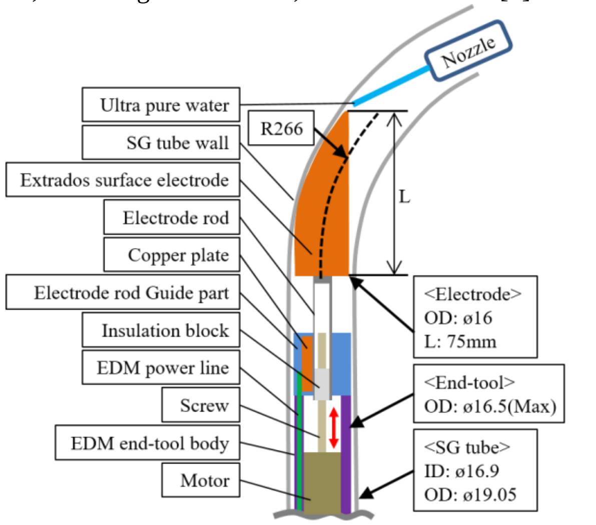

Fig. 4 Schematic of In-bore EDM end-tool design.

Table I: Process variable of EDM

Parameter	Value
Peak current	15 A
Input voltage	100 V
Pulse on time	200 μs
Pulse off time	113 μs

Secondly, to transfer the necessary elements for EDM to the target location, we developed an in-bore type transport tool and device. By using a Pusher, these tools can extend up to 20 meters in length when attached to a Teflon tube that is connected both outside and inside the water chamber. Additionally, we established a power connector capable of transmitting up to 2kW of power.

Based on the results of underwater EDM experiments using this technology, the detailed EDM process variables were finally derived in a real SG tube with an inner diameter of Ø 16.9mm R264 bending (Table I).

3. EDM test for prototype

According to the prototype testing conditions, the in-bore EDM process was applied to the steam generator heat exchange tubes bent to a radius of 264mm. The end tool was inserted into the SG tube installed in the unit mock-up facility using a cable pusher and manually moved to the target position (Fig. 5). This process requires automation improvements that enable precise and automatic transportation of the in-bore EDM end tool to the specified target position. Upon reaching the target position, the clamping mechanism of the in-bore EDM end tool is activated, ensuring a secure fixation to inner wall of the SG tube.

The device attachment process reduces the impact of external disturbances, such as external vibrations, and prevents positional variations caused by tube cable compression and expansion. EDM end-tool was equipped with a silicone O-ring to enhance friction and reinforce its attachment to the inner wall of the SG tube.

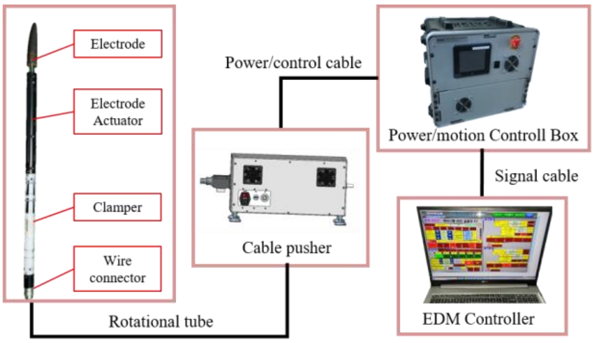

Fig. 5 Set-up of the in-bore electrical discharge machining test for bending SG tube.

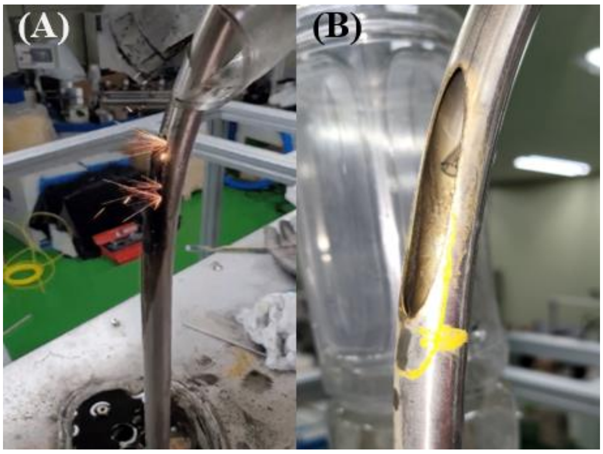

Fig. 6 EDM test for SG tube (A) Debris scattering (B) Window in bending zone

After the end tool fixation, a tube for supplying ultra-pure water(resistivity: 18.2 MΩ cm) is inserted into the passage of the heat exchange tube on the opposite side where the device is inserted. This ultra-pure water is supplied as the dielectric fluid for the in-bore EDM process. Under the ultra-pure water supply environment, EDM process was executed using the optimized machining parameters (Table I) that were previously optimized for Inconel 690 material in underwater conditions (Fig. 6).

4. Conclusions

EDM processing debris was collected from the Inconel 690 heat transfer tubes currently in use in the steam generators of APR1400 standard nuclear power plants. The size of the collected debris powder conforms to the standards approved by the Korea Institute of Nuclear Safety (KINS), offering a new in-bore remote maintenance method for the SG tube in nuclear power plant steam generators (Fig 7). This end-tool, equipped with ultra-miniaturized in-bore EDM technology and designed with an optimal electrode in terms of size and shape, can be inserted through the primary side tube sheet of the SG tube to accurately reach the target location. It ensures the removal of the foreign object without generating additional materials and safely exits to the steam generator's primary side water chamber, where the operator is located. The results of this study suggest that by applying hardware robustness and optimal control to the in-bore end-tool, the processing time is expected to be reduced (Table II).

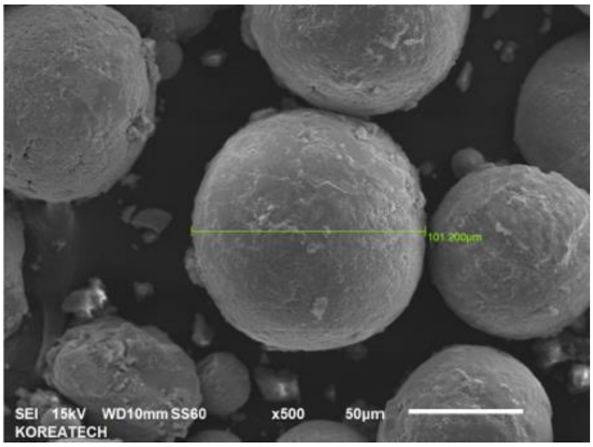

Fig. 7 Particle size of Debris for SG tube

Table II: Result of EDM for SG tube

Result	Value
Removed Volume	1220 mm^3
Net EDM Time	44.8 h
Material Removal Rate	27.2 (mm^3/h)

We have proposed an innovative remote maintenance method that can enhance the operational robustness of nuclear power plants worldwide. It also demonstrates the potential for application in in-bore remote maintenance robotic technology, which could become a fundamental core technology for pipe cutting and welding in future nuclear fusion power blanket modules.

REFERENCES

[1] D.R. Diercks a, W.J. Shack a, J. Muscara, Overview of steam generator tube degradation and integrity issues, Nuclear Engineering and Design, 1997.
[2] L. Obrutsky, Jovica Riznic, Steam Generators for Nuclear Power Plants, Elsevier, pp.495-510, 2017.
[3] Matej Pleterski, Josko Valentincic, Izidor Sabotin, Heat Exchanger Tube Cutting System, 24th International Conference Nuclear Energy for New Europe, Sep.14-17, 2015, Portoroz, Slovenia.