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Prototype Development of a Repair Welding Robot with Three-Dimensional Trajectory Tracking for Large-Diameter Piping

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1. Introduction

The Reactor Coolant System (RCS) piping is one of the major pressure-boundary components in nuclear power plants. As nuclear power plants are operated for long periods, welds in large-diameter RCS piping may be affected by thermal fatigue, residual stress, local deformation, and degradation of the weld metal and heat-affected zone. When cracking or deformation is suspected in an RCS pipe weld, nondestructive examination is generally performed first. However, local boat sampling may be required to directly evaluate the material condition around the suspected defect.

Boat sampling is a process in which a specimen is locally extracted from the weld metal or heat-affected zone for material evaluation. In this process, a specimen having a certain width, length, and depth is removed from the pipe surface, and an empty space remains after sampling. In this study, the local depression or groove-shaped remaining space formed on the pipe surface after specimen extraction is defined as a Cavity.

The shape of the Cavity may vary depending on the size of the extracted specimen, EDM machining path, and machined surface condition. In addition, irregularity may be added to the Cavity surface during grinding, which is performed before repair welding to remove oxide layers, recast layers, and machining residues. Therefore, the Cavity remaining after boat sampling is not an ideal trapezoidal groove or a simple shape with constant curvature, but can appear as an irregular three-dimensional curved surface whose depth varies depending on location.

In this study, an automated temper bead repair welding robot based on three-dimensional scan data is proposed for the Cavity formed in a boat-sampled RCS pipe weld [2]. This study aims to advance the three-degree-of-freedom EDM robot technology for curved specimen extraction and the Cavity 3D scan data utilization technology secured through the previous research project, “Development of a 3-DOF EDM Robot for Curved Specimen Extraction from Nuclear Components,” and apply them to the repair welding process [1].

While the previous study focused on performing boat sampling on curved nuclear component surfaces and measuring the shape of the Cavity formed after sampling, this study focuses on automatically generating a repair welding trajectory based on the measured 3D Cavity geometry and automatically performing temper bead repair welding along the generated trajectory. For this purpose, the proposed system is configured to control torch movement, arc length, and bead overlap ratio using the reconstructed curved surface data.

The direct development scope of this project is limited to the Cavity repair welding robot after boat sampling. However, when the technology proposed in this study is integrated with the previously developed 3-DOF EDM robot and Cavity scanning technology, it can be expanded into an integrated maintenance platform that continuously performs defect evaluation, boat sampling, Cavity shape measurement, and automated temper bead repair welding. Therefore, this study can serve as a fundamental technology for automating the process from specimen extraction to restoration of aged nuclear power plant components.

2. Methods and Results

2.1 System Configuration

In this study, a system was configured to connect Cavity shape measurement and temper bead repair welding. Fig. 1 shows the configuration of the system.

The system consists of a robot on which the scanner and torch can be mounted simultaneously or interchangeably, an integrated control PC, a motion/welding controller, and a GTAW welding power source.

The scanner-mounted robot is a device for measuring the Cavity surface. It receives robot position control signals from the motion/welding controller and adjusts the position of the scanner. The Cavity shape data acquired through the scanner are transmitted to the integrated control PC, where the Cavity cross-section and three-dimensional shape are checked based on the measured data.

The torch-mounted robot is equipped with the gas supply line, filler wire supply line, and tungsten tip required for GTAW welding. It also receives robot position control signals from the motion/welding controller and moves along the predefined trajectory.

The GTAW welding power source supplies welding power and shielding gas to the torch-mounted robot and exchanges welding control signals and current/voltage feedback signals with the motion/welding controller.

The motion/welding controller acts as an intermediate control unit between the integrated control PC, the robot, and the welding power source. It controls the robot transfer axes according to the scanning and welding sequences. During the scanning process, it controls the scanner position to acquire Cavity shape data. During the welding process, it moves the torch-mounted robot along the generated trajectory. In addition, it controls welding start and stop, output control, and acquisition of current and voltage measurements in connection with the GTAW welding power source, thereby monitoring the welding state and transmitting process data to the PC.

The integrated control PC manages scanning control and welding sequences. Through this configuration, Cavity shape measurement, welding trajectory generation, welding execution, and post-weld shape comparison are connected as a single experimental procedure.

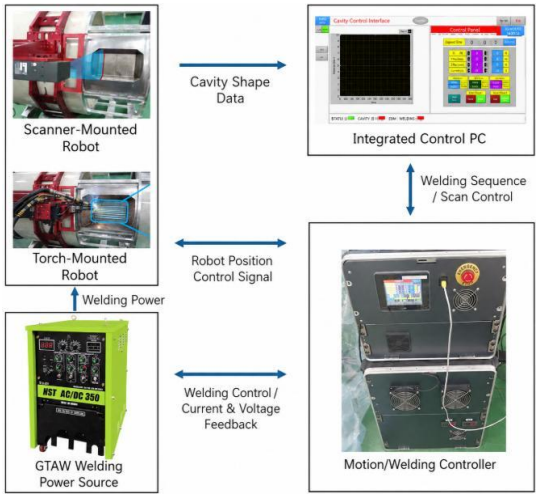


Fig 1. System configuration of the 3D Cavity scanning and automated temper bead repair welding robot.

2.2 Parameter Setting

Prior to the repair welding experiment, preliminary welding tests were performed by varying the welding current, filler wire feed speed, tungsten tip protrusion length, and pass interval in order to select appropriate welding parameters. Figs. 2 to 5 show the appearance of the weld beads formed under each condition. The preliminary test was divided into four cases, and the bead shape, melting condition, oxidation occurrence, and overlap condition between passes were compared for each case.



Fig 2 . Case #1



Fig 3. Case #2



Fig 4. Case #3



Fig 5. Case #4

Under the Case #1 condition, excessive melting occurred, resulting in an unstable bead shape and an overheated surface. To improve the excessive melting, the welding current was reduced in Case #2. However, the heat input was insufficient relative to the filler wire feed amount, so the bead was not sufficiently melted, and the fusion between passes and the surface shape were not uniform.

In Case #3, the filler wire feed speed was reduced, which partially improved the insufficient melting observed in Case #2. However, oxidation occurred on the bead surface. This was judged to indicate that improvement of the shielding gas protection range was required.

In Case #4, the tungsten tip protrusion length was reduced to improve the shielding gas protection range and arc stability. As a result, the surface oxidation observed in Case #3 was reduced, and the bead surface condition and bead geometry were relatively improved. However, it was confirmed that the step interval should be adjusted to sufficiently secure the overlap ratio between passes for a bead width of 7 mm.

Therefore, the final parameters were selected based on the Case #4 condition. In temper bead repair welding, securing the overlap ratio between the previous and subsequent passes is important. Therefore, the step interval was modified from the initial 5 mm to 3.5 mm to satisfy an overlap ratio of approximately 50% based on a bead width of 7 mm.

Case No.	**Welding Current (A)**	**Feed Speed (mm/s)**	**Tip Protrusion (mm)**	**Bead Width (mm)**
#1	170	4	10	-
#2	110	4	10	-
#3	110	2	10	7
#4	110	2	5	7

Table I. Comparison of preliminary welding test conditions and results

The repair welding experiment was performed based on the Case #4 condition selected through the preliminary test. Welding and scanning were repeatedly performed under the same welding condition, and the shape change after deposition and the height difference

by section were compared. The main parameters used in this experiment are shown in Table II.

Welding parameters	Welding current: 110 A/ 3 Hz/ 50 %duty Start and crater current: 70 A Base metal: SC45 / 6T Filler metal: ER70S-6 / 1.6 mm Shielding gas flow rate: 20 L/min Upslope and downslope time: 2 sec
Robot parameters	Travel speed: 1 mm/s Positioning resolution: 0.001 mm Filler wire feed speed: 2 mm/s Arc distance: 4 mm Tip protrusion length: 5 mm Torch angle: 90 ° Bead width: 7 mm/ 50% overlap Path: 40 x 3.5(mm) repeated 4 times

Table II. Final selected welding and robot parameters

The purpose of this experiment was not to finalize the repair welding quality, but to determine whether bead height and cross-sectional shape changes could be quantitatively compared from scan data when welding was repeated under the same parameters. In the current preliminary welding test, no excessive oxidation, overheating discoloration, or clear surface defects were observed on the bead surface based on visual inspection. Therefore, at this stage, the applicability of the welding and measurement procedure was primarily examined through scan-based shape comparison and visual inspection.

In future work, after filling welding is completed on a Cavity mock-up, the repair weld section will be cut and submitted to external testing and advisory organizations. Penetration, interlayer fusion, porosity, cracks, hardness distribution, and metallurgical microstructure will be evaluated to quantitatively verify the actual repair welding quality.

2.3 Scanning after the First Welding Pass

Fig. 6 shows the measurement of the bead shape using a scanning sensor after welding. The scanning sensor projects a laser line across the upper surface of the weld bead and measures the surface height difference between the bead and the surrounding base metal. The measured cross-sectional data are transmitted to the integrated control PC and converted into two-dimensional cross-sectional data or three-dimensional shape data.

Fig. 7 shows the three-dimensional scan result acquired after the first welding pass. In the measured result, the weld bead appears as a region higher than the surrounding base metal surface, and the height difference between the bead center and edge regions is distinguished by color. The 3D scan data can be used to confirm the bead shape in the longitudinal direction, the cross-section in the width direction, the edge slope, and local height variations.

These scan results are important for automation of repair welding. In temper bead repair welding, subsequent passes must be arranged on the previous pass with a certain overlap ratio. For this purpose, the actual height and width of the previous bead must be identified. Therefore, by performing 3D scanning after welding, basic data can be obtained for correcting the torch height, spacing between passes, and bead overlap ratio for the subsequent pass.



Fig 6 Scanning process after welding.

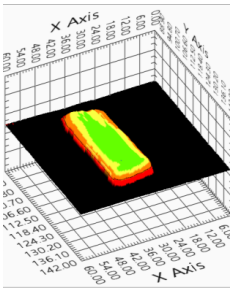


Fig 7 Three-dimensional scan data after the first welding pass.

After welding and scanning were repeatedly performed under the same welding parameters, the scan data from each pass were compared. Fig. 8 shows the comparison of 3D scan cross-sectional data for the same section. The X-axis of the graph represents the measurement position, and the Z-axis represents the surface height. In this graph, the orange line represents the scan data after the first welding pass, and the yellow line represents the scan data after the second welding pass.

As a result of the data comparison, the yellow data measured after the second welding pass showed overall higher values than the orange data measured after the first welding pass in the bead-formed region. This indicates that the weld bead accumulated as welding was repeated under the same parameters. It also shows that the height change caused by bead deposition can be quantitatively identified using scan data. In particular, the height difference between the first and second welding data was clearly observed at the bead center, allowing comparison of the increase in deposition height caused by repeated welding. This result can be linked to bead build-up, overlap ratio, and grinding amount management required in temper bead welding [2].

In addition, a region where the height decreases outside the bead area was observed on the left side of the graph. This region corresponds to the outer edge of the base metal, and it is considered that the base metal locally underwent thermal deformation and shrinkage due to welding heat input. In other words, the 3D scan cross-sectional data can be used not only to measure the height change of the weld bead itself, but also to identify deformation occurring in the surrounding base metal due to welding heat.

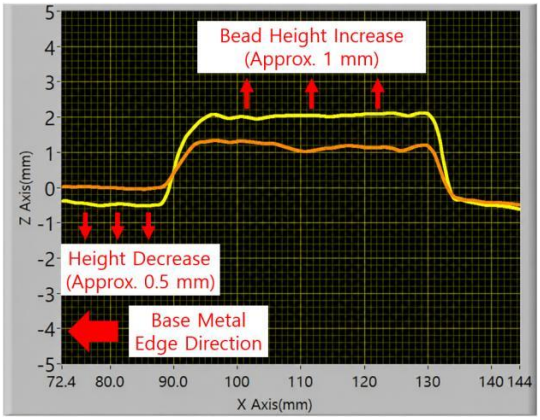


Fig. 8. Comparison of scan data after repeated welding.

3. Conclusions

In this study, the applicability of an automated temper bead repair welding system based on 3D scan data was examined for the Cavity formed in a boat-sampled RCS pipe weld. The proposed system was configured so that Cavity shape measurement, welding execution, post-weld rescanning, and cross-sectional shape comparison could be connected as a single procedure.

As a result of the preliminary experiment, when welding was repeated under the same welding parameters, the bead build-up height and cross-sectional shape changes could be quantitatively identified using 3D scan data. In particular, by comparing the scan data after the first and second welding passes, the increase in height due to bead deposition was confirmed. Local deformation occurring in the surrounding base metal due to welding heat input was also identified through the cross-sectional graph. This indicates that post-weld scan data can be used not only for shape inspection, but also for deposition amount management, grinding removal amount confirmation, thermal deformation evaluation, and subsequent pass correction.

At the current stage, the weld quality was evaluated based on visual inspection, and no excessive oxidation, overheating discoloration, or clear surface defects were observed on the bead surface. In future work, actual filling welding will be performed on a Cavity mock-up. The repair weld section will then be cut, and penetration, interlayer fusion, porosity, cracks, hardness distribution, and metallurgical microstructure will be quantitatively evaluated through external testing and advisory organizations [3].

Finally, the results of this study demonstrate the possibility of automatic trajectory generation and shape feedback control using 3D scan data in the Cavity repair welding process after boat sampling. If a closed-loop correction algorithm linking scan data with welding current, voltage, travel speed, and filler wire feed conditions is established in the future, the proposed system is expected to be expanded into a remote automated maintenance platform that connects Cavity measurement and temper bead repair welding for aged nuclear RCS pipe welds.

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