applied sciences

MDPI

Technical Note

Analysis of Foreign Substance Flow within the Weld Joint through Simulation in Pressurized Water Reactor Nuclear Fuel Rods

Taehyung Na, Taehyeon Kim and Yongdeog Kim *

Korea Hydro & Nuclear Power Central Research Institute, 70 Youseong daero 1312, Daejeon 34101, Republic of Korea; taehyung.na@khnp.co.kr (T.N.); taehyeon.kim@khnp.co.kr (T.K.)
* Correspondence: yongdkim@khnp.co.kr

Abstract: The welding of end plugs to cladding tubes is a critical process in the manufacture of pressurized water reactor (PWR) nuclear fuel rods. The resistance butt welding method is commonly used for this purpose in production. In this paper, we present an analysis of the flow of foreign substances within the weld joint during the tube-cap welding process of PWR nuclear fuel rods, using SORPAS 2D software. The welding process generates foreign substances such as oxide scales, welding fumes, and spatters, which can negatively impact the quality of the weld. Additionally, carbide-based ceramic materials with higher melting temperatures than the base metal have been found within the weld joint in some cases, which can also affect the quality of the weld. To simulate the intrusion of foreign substances with higher melting temperatures than the base material (zirconium alloy) during welding, we conducted a simulation and analyzed the flow of foreign substances. Based on this study, we expected to enhance the reliability and stability of the tube-cap welding process of PWR nuclear fuel rods.

Keywords: foreign substance flow; nuclear fuel rods; resistance butt welding; zirconium alloy

check for updates

Citation: Na, T.; Kim, T.; Kim, Y. Analysis of Foreign Substance Flow within the Weld Joint through Simulation in Pressurized Water Reactor Nuclear Fuel Rods. *Appl. Sci.* **2023**, *13*, 8905. https://doi.org/10.3390/app13158905

Academic Editors: Dariusz Fydrych, Jacek Tomków, Grzegorz Rogalski, Hamed Aghajani Derazkola, Aleksandra Świerczyńska, Sergey G. Parshin, Chandan Pandey, Michał Landowski and Thomas Hassel

Received: 12 May 2023
Revised: 31 July 2023
Accepted: 1 August 2023
Published: 2 August 2023

1. Introduction

Tube-cap welding is a welding technique primarily used to seal pipes and tubes with a cap. It is commonly performed using either resistance welding or arc welding methods. Worldwide, this welding method is widely employed in the manufacturing of nuclear fuels to seal radioactive material, such as UO2, within the fuel rod's interior. The welding method between the cladding tube and the end plug used to manufacture fuel rods in domestic uses is the resistance butt welding method [1–3]. The welding time is very short (one cycle, 16.67 ms), and the welding temperature is lower than that of arc welding, so the heat-affected zone is small and productive. Moreover, there is an effect of pushing foreign substances outside the weld joint. The external weld reinforcement (bead) formed outside the cladding tube thickness is subsequently removed through machining after welding.

However, resistance butt welding carries the risk of radioactive material leakage from the welded joint due to various factors, such as the presence of radioactive substances generated by uranium fission, foreign substances, or defects in the weld, as well as stress concentration caused by plastic deformation. Therefore, it is crucial to accurately understand the welding mechanism/phenomena and ensure the reliability of the welded joint through various soundness confirmation tests [4–7].

In general, the integrity of the resistance welds is verified through the burst test and macrograph test, which are the destruction tests, before and after the fuel rods are produced. When testing for integrity, there have been cases where carbide-based ceramic material with a higher melting temperature than the base metal has been found in the weld joint, and such material may affect the quality of the weld [8]. The purpose of this study is to find the optimal welding conditions for moving these foreign substances to the outer part of the tube. After the actual welding test, the phenomenon was attempted to be reproduced through a macrograph test, but it is very difficult to identify foreign substances in the welding part because only one section of the welding part formed in the circumferential direction can be identified.

In an attempt to overcome this limitation, a recent study carried out a simulation of a resistance butt welding process and used the results to investigate the effect of various variable factors on the welding process. In this study, it is assumed that there is a foreign substance with a higher melting temperature than the base material in the joint, and tube-cap welding simulations were performed for different current conditions to predict the optimum conditions for the foreign substance to move (flow) and migrate to the external reinforcement, which is excluded from the joint criteria. And the location of the foreign material was compared with the simulation results using a macrograph of the actual tube-cap weld.

2. Resistance Butt Welding

Resistance butt welding is a joining process in which the contact surface between two materials is melted using the resistance heat generated when a current is passed through the two stacked materials under pressure. The mechanism of this process is based on Joule's Law, as shown in Equation (1) [9].

$$Q = I^2 R t \tag{1}$$

Here, Q is the amount of heat (J), I is the welding current (A), R is the electrical resistance (Ω), and t is the current passing time (s). The amount of heat generated in resistance welding is proportional to the square of the applied current, the combined electrical resistance, and the current passing time. As current passing time is a factor that significantly affects the process cost—i.e., productivity—the shorter the time, the better. In addition, even a small variation in current can have a large effect on the process. Electrical resistance is generally divided into contact resistance and intrinsic resistance. Intrinsic resistance is influenced by the dimension (length and cross-sectional area of the passage) connecting the electrode to the base material through which the current flows, while contact resistance is determined by the pressure exerted on the electrode.

3. Simulation of Tube-Cap Welding

SORPAS 2D, a simulation software package for resistance welding, was used to simulate the resistance butt welding process [10–14].

3.1. Tube-Cap Welding for Nuclear Fuel Rod

The Tube-cap welding of the fuel rod employs the resistance butt welding method. As shown in Figure 1, the end plug and the cladding tube are fixed as separate electrodes, and a force is applied to the end plug to bring it into contact with the cladding tube. Subsequently, the welding process begins, during which a squeeze time (20 cycles) is applied due to the applied pressure, and welding occurs as the current flows for 1 cycle. At this stage, the length of the cladding tube protruding from the CT electrode is referred to as the overlapping length (O.L), and it forms the welded joint as it joins with the end plug. Following the welding process, external reinforcement (bead) is generated based on the shape of the tube electrode, and this section is then machined to remove the reinforcement [15–18].

3.2. Simulation Process

In this study, the change in shape according to the temperature of the welding part and plastic deformation in electrical resistance welding was simulated by analysis, and for this study, an electro-thermal-mechanical combination model was applied as shown in Figure 2. In addition, transient simulation was applied to calculate each coupled model according to the detailed time step to derive changes in the finely changing physical properties and results.

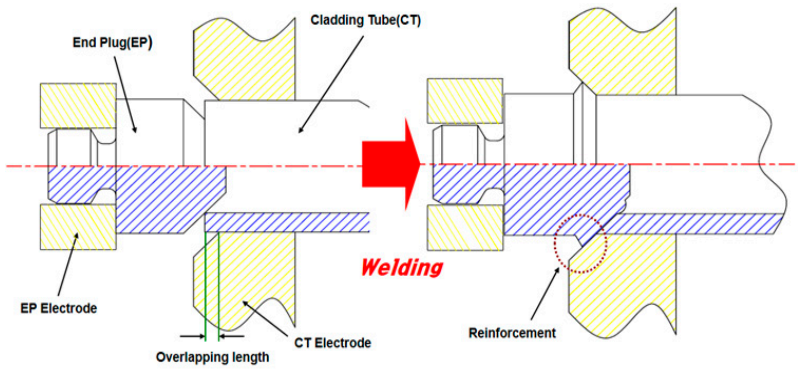

Figure 1. Tube-cap welding diagram for fuel rod.

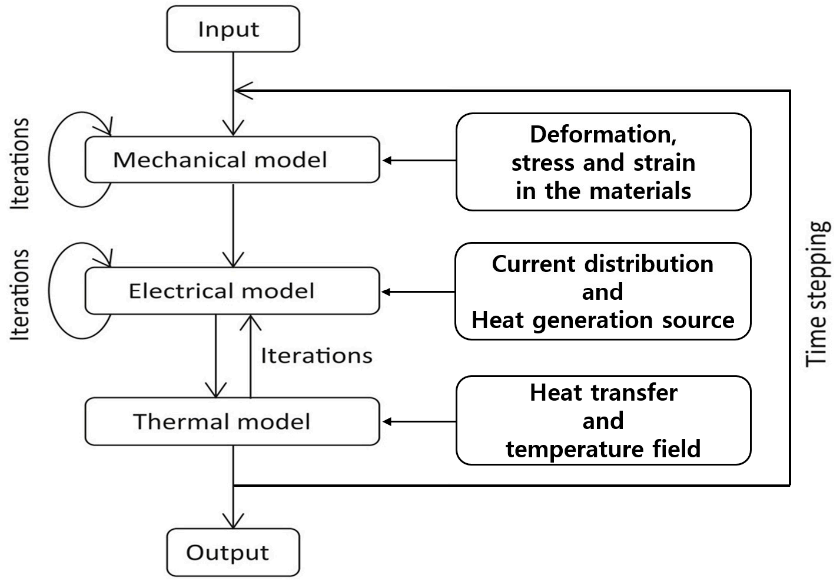

Figure 2. Process of simulation for welding.

The process that proceeds as the interpretation is coupled is as follows. First of all, in the initial stage, the end plug and cladding tube are contacted by pressure during squeeze time, so only the mechanical model is applied to calculate the speed field and overall stress of the end plug and cladding tube. However, after contact between the two objects is made, three models are combined to perform a resistance welding analysis. The main coupling process of the three models is as follows. The electrical model allows the input current value to calculate the distribution of the current density, and the thermal model calculates the resistance heat generation obtained from the electrical model and the resulting temperature distribution. The mechanical model calculates the material property value change and plastic deformation depending on the temperature distribution of the welding part calculated in the thermal model. The contact area between objects obtained from the mechanical model is applied again as an input value of current density, and the coupling process for the three models is repeated until the analysis is completed. In this study, the time step of each iteration was applied to 10 µs or less so that the analysis result of the resistance welding applying the AC welding current of 60 Hz could be well converged [11–16].

$$\int_V \overline{\sigma}\delta\dot{\overline{\varepsilon}}dV + K\int_V \dot{\varepsilon}_{ii}\delta\dot{\varepsilon}_{jj}dV - \int_{S_t} t_i\delta u_j dS + \delta\Pi_C = 0 \tag{2}$$

$$\int_V \Phi_j \delta\Phi_j dV - \int_{S_t} \Phi_n dS + \delta\Pi_\Phi = 0 \quad (3)$$

$$\int_V k\mathrm{T}_j \delta\mathrm{T}_j dV + \int_V \rho_m c_m \dot{T} \delta T dV - \int_V \dot{q}_V \delta T dV - \int_{S_t} \dot{q}_S dS + \delta\Pi_T = 0 \quad (4)$$

The governing equation for the mechanical model is shown in Equation (2) and is mainly used to calculate shape changes due to plastic deformation. The governing equation can be used to calculate the contact area, internal stress, plastic deformation energy, friction, and heat generation. The electrical potential (Φ) is an important variable in the electrical model and its governing equation is expressed as a Laplace equation in Equation (3). The thermal model follows the Galerkin heat transfer equation and is expressed in Equation (4). Table 1 shows the nomenclature of symbols used in governing equations.

Table 1. Properties used in the simulations.

Symbol	Nomenclature	Symbol	Nomenclature
$\overline{\sigma}$	Effective stress	k	Thermal conductivity
$\dot{\overline{\varepsilon}}$	Effective plastic strain rate	ρ_m	Mass density
K	Large positive number	c_m	Heat capacity
$\dot{\varepsilon}_{ii}$	Volumetric strain rate	$\dot{T}$	Temperature rate
t_i	Surface traction	$\dot{q}_V$	Heat generation rate in volume
u_i	Velocity on the surface	$\dot{q}_S$	Heat generation rate along surface
Φ	Electric potential		

3.3. Simulation Steps

3.3.1. Modeling and Material Used

Zirconium alloys, widely used as materials for nuclear fuel rods, were used in the present study. The materials of each component are shown in Tables 2–4 provide a summary of the chemical composition and mechanical properties of these materials. The selected welding method was resistance butt welding, and the simulation was performed using an axisymmetric model as shown in Figure 3. The number of each component shown in the diagram of Figure 1 matches the components of the number shown in Table 2.

3.3.2. Simulation Modeling and Material Used

The main parameter used in the simulation was the current (A), as shown in Table 5. The fixed parameters were set as follows: the squeeze time, which refers to the duration of the application of the initial pressure, was set to 20 cycles; the welding time, such as the time during which the current flows, was set to 1 cycle; and the holding time, which is the time during which the applied pressure is maintained after the welding time, was set to 5 cycles. A 60 Hz single-phase AC thyristor welding machine was used in the welding process.

Table 2. Materials used in the simulation.

No.	Components	Material
1	Cladding Tube (CT)	ZIRLO
2	CT Electrode	CuBe2
3	End Plug (EP)	Zircaloy-4
4	EP Electrode	$CuBe_2$

Table 3. Chemical composition of the used material (%) [19].

Type	Sn	Fe	Cr	Nb	O	Zr
ZIRLO	1.20	0.120	-	1.0	0.120	Bal
Zircaloy4	1.30	0.220	0.10	-	0.120	Bal

Table 4. Mechanical properties of the used material (%) [19].

Type	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Poisson's Ratio	Melting Point (°C)
ZIRLO	613.88	819.04	14.67	0.10	1834
Zircaloy4	597.50	794.40	15.6	0.18	1834

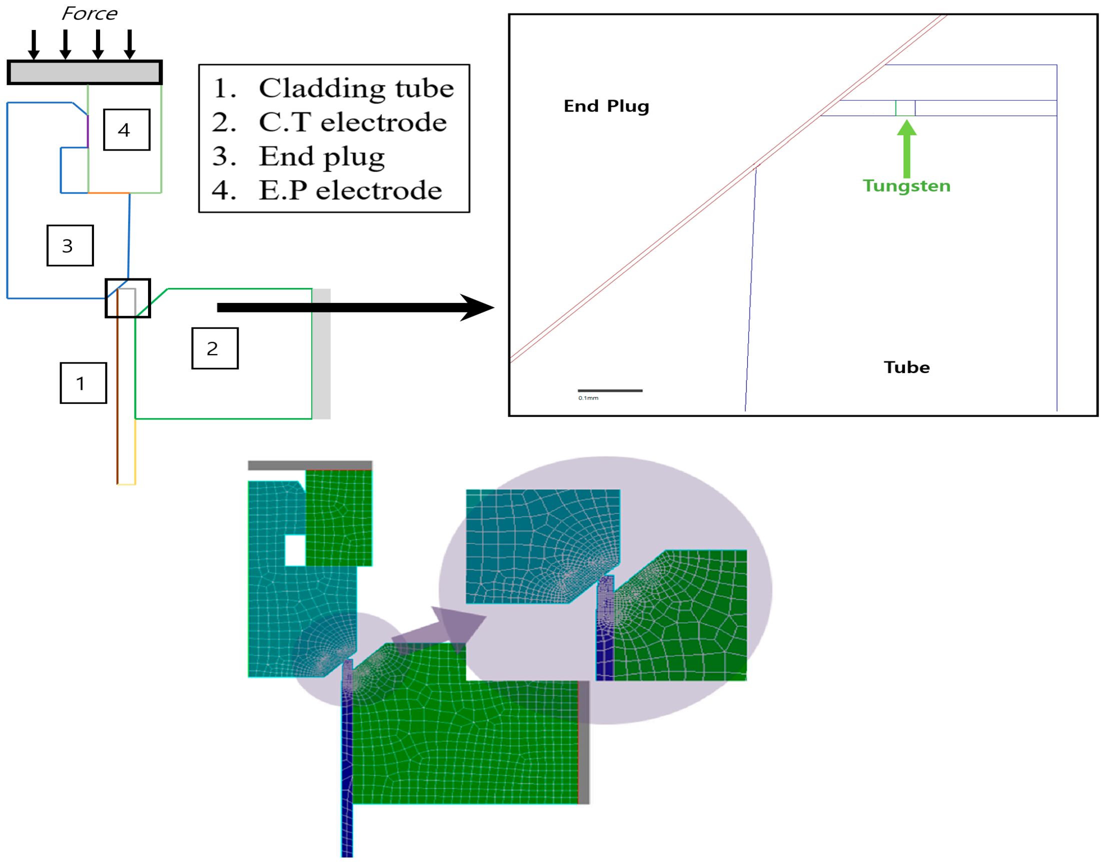

Figure 3. Simulation modeling and location of substance (tungsten).

Table 5. Variable factor for butt welding.

Factor	Range			
Over lapping (mm)	0.8 (fixed)			
Force (kN)	4.3 (fixed)			
Current (kA)	11	12	14	15

According to the analysis of the previous nuclear fuel rod welding, significant resistance occurred during the first half cycle of one cycle, resulting in a large amount of heat generation [15,16]. In addition, the welding temperature exceeded the melting temperature of the material, causing the material to melt. Based on the fact that this period is a critical factor during the entire welding process. To analyze this flow phenomenon, Figure 3 assumes that a foreign substance (tungsten) with a melting temperature higher than the melting temperature is included in the tube material and analyzes how this foreign substance moves within the weld pass depending on the welding variables. It is assumed that the foreign substance is introduced into the tube rather than the end plug (cap), as the tube undergoes significant melting and shape changes compared to the end plug. Table 6 shows the melting temperatures of the materials used, including the end plug, the tube, and the foreign substance (tungsten).

Table 6. Melting temperature.

Object	Material	Solidus (°C)	Liquidus (°C)
Cladding Tube	ZIRLO	1834	1834
End plug (cap)	Zircaloy-4	1834	1834
Foreign substance	Tungsten	3400	3422

The displacement of the substance was measured by setting the green dot (tungsten) inside the tube as the initial position and measuring the displacement of the substance during the welding process with respect to this position, as shown in Figure 4. In addition, the measurement intervals for analyzing the position of the foreign substance during welding were shown, and the welding time was divided into five intervals, with the first half cycle divided into four intervals and the remaining one interval being the point at which welding ended. This is based on the previous analysis, which suggests that welding temperature and electrode displacement, as well as significant resistance, mainly occur during the first half cycle [15,16]. Horizontal movement distance dx, vertical movement distance dy, and diagonal movement distance dx + dy were designated to measure the movement position of the foreign substances at each point of 1~5 during welding.

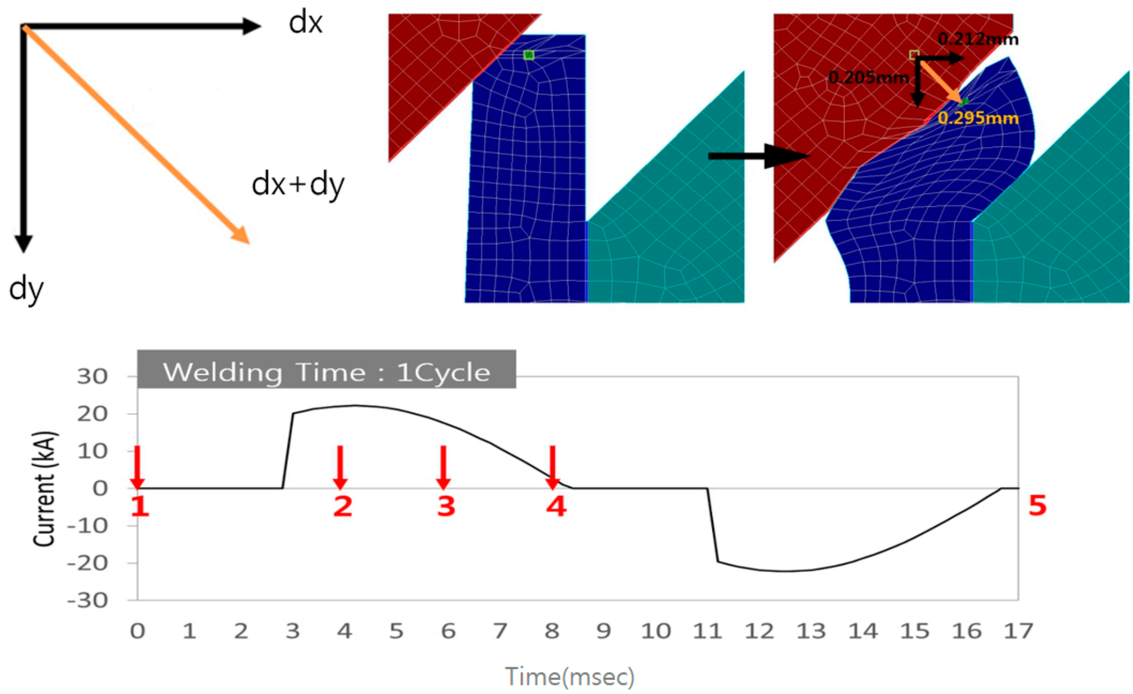

Figure 4. Measurement section of foreign substance (weld time of one cycle).

4. Simulation and Analysis of Substance Flow

The welding variables for the tube-cap welding of nuclear fuel rods are current, force, and overlap length (O.L). Among these, force and O.L were fixed (pressure 4.3 kN, O.L 0.8 mm), and the current varied during the simulation. The current was changed to 11 kA, 12 kA, 13 kA, and 15 kA to perform the simulation. Through previous analysis and experiments, it was determined that the current value at which the weld is completely melted is 14 kA [15,16].

4.1. Results of Current 11 kA and 12 kA

Figure 5 shows the simulation result for a current condition of 11 kA, while Figure 6 shows the result for a current condition of 12 kA. Analyzing the welding status for both conditions, it can be seen that the heat input was not sufficient to produce melting in the weld joint. Only a solid phase weld, produced by the application of pressure and a certain amount of heat, was achieved, but the outer part of the tube was not welded. An analysis of the foreign substance (tungsten) flow results at the six specified measurement points showed that it remained inside the tube. However, the foreign substance moved slightly towards the outer edge (x- and y-axis direction) under the 12 kA condition compared to the 11 kA condition. This is because the heat input was not sufficient to cause melting in the weld, and the external weld reinforcement was not sufficient to allow sufficient flow for the impurity to escape through the thickness of the tube. When evaluating the change in impurity movement, it was found that the change in impurity position between point 1, where welding begins, and point 4, where the first half cycle ends, was significant, while the change in impurity position between point 4, where the first half cycle ends, and point 5, where the second half cycle ends and welding is completed, was not significant.

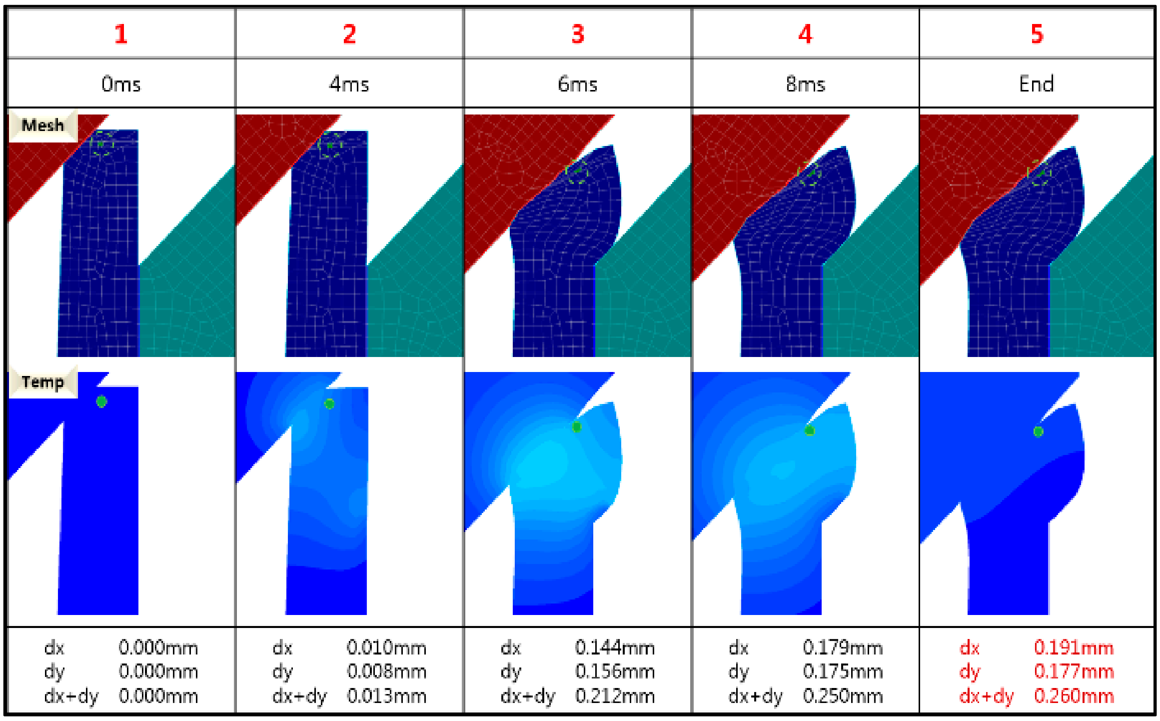

Figure 5. Location of the foreign substance (11 kA).

4.2. Results of Current 14 kA

Figure 7 shows the simulation results with a current condition of 14 kA. The weld was fully formed to the thickness of the tube, and a large amount of external weld reinforcement was formed. An analysis of foreign substance movement outside the tube was carried out when evaluating the amount of foreign substance movement. Most of the movement occurred in the first half-cycle section, and there was almost no movement in the second half-cycle section. Because even if the current is passed again in the second half-cycle section after the cooling time section, the resistance will not be significant as the joint of the material becomes larger after the first half-cycle section. Therefore, as no melting and no significant flow can occur, there has not been much foreign substance flow. The part where melting occurs in the welding part is indicated in gray in the simulation.

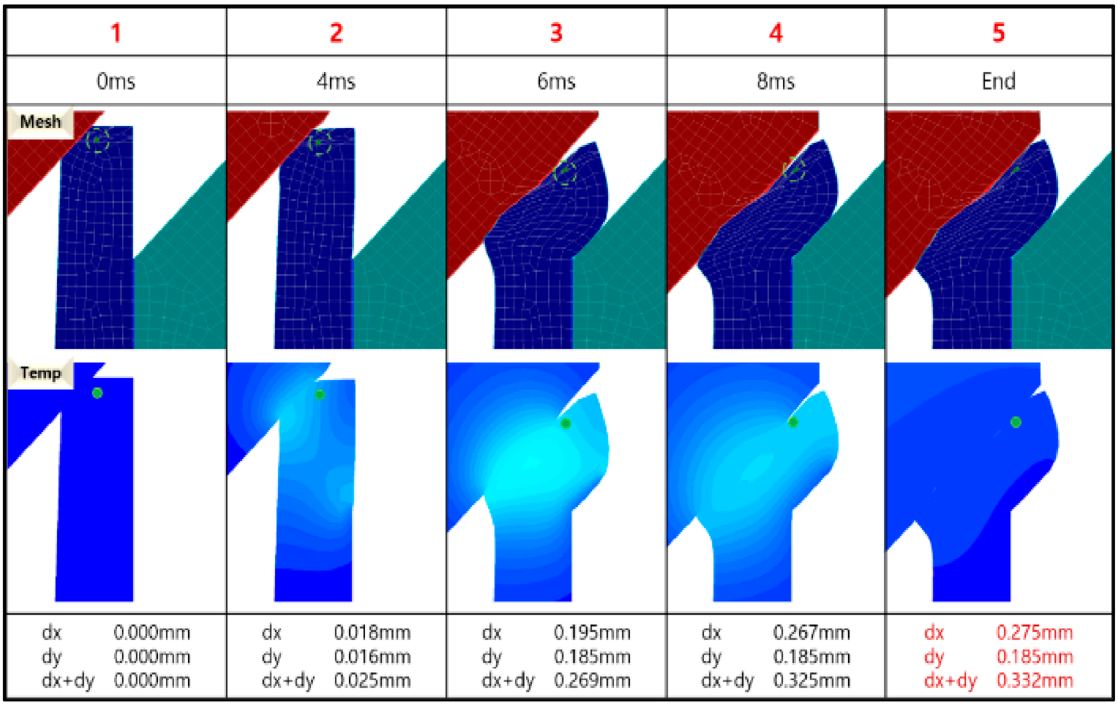

Figure 6. Location of the foreign substance (12 kA).

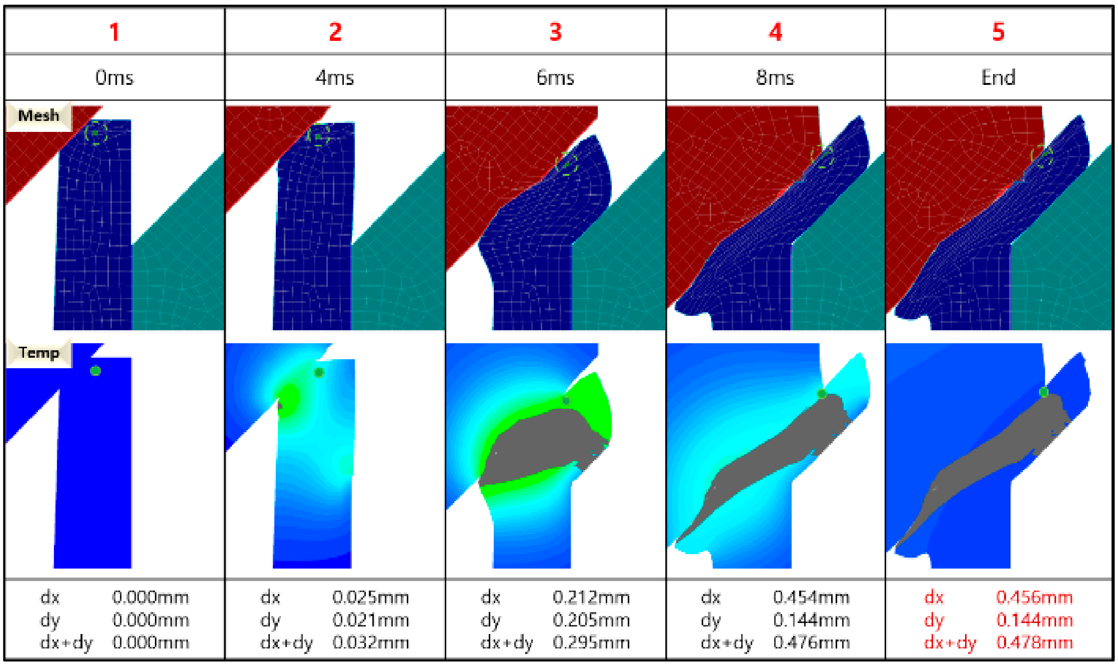

Figure 7. Location of the foreign substance (14 kA).

4.3. Results of Current 15 kA

Figure 8 shows the simulation results with the current condition set to 15 kA. As can be seen from the results, the heat input is high, and the welding temperature exceeds the melting temperature of the material, resulting in an almost complete melting of the entire weld joint including the weld bead. In the actual tube-cap weld under these conditions, over-welding occurred, resulting in melting on the surface of the weld joint. An analysis of the foreign substance flow results of the designated measurement section of six sections showed that it flowed out of the tube. The amount of foreign material movement is similar to the 14 kA condition, but it moved more in the X and Y directions.

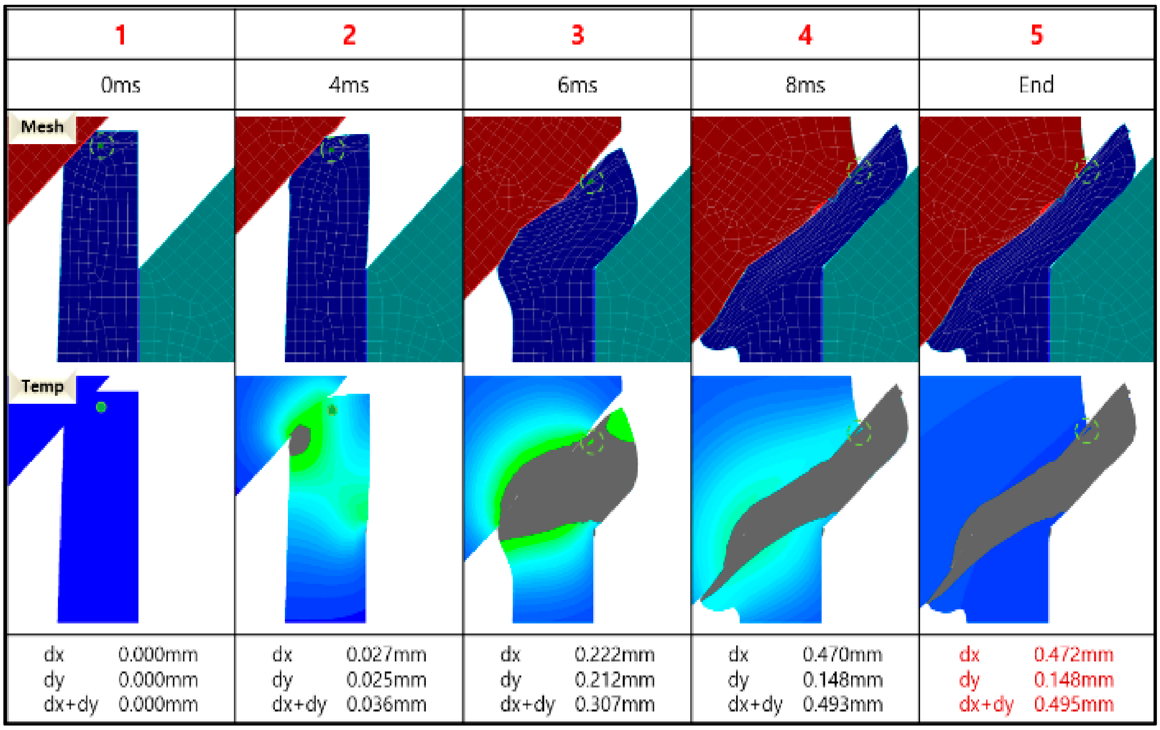

Figure 8. Location of the foreign substance (15 kA).

5. Reliability of Simulation

It is necessary to verify the reliability of the simulation results of tube-cap welding tests using resistance butt welding so that the simulation results obtained can replace the experimental results. The reliability of the resistance butt welding simulation program used in this study has been reported in previous studies [15–18]. In order to verify the simulation results of the substance flow, a tungsten piece of about 10 μm was attached to the center of the tube end that contacts the end plug before welding under the welding condition of 14 kA. After the welding test, the weld section was examined using a macrograph test. Figure 9 shows a cross-section of the weld where the substance appeared at the end of the outer weld bead, which is similar to the position shown in the simulation results. Therefore, the simulation results obtained were considered valid to replace the experimental results.

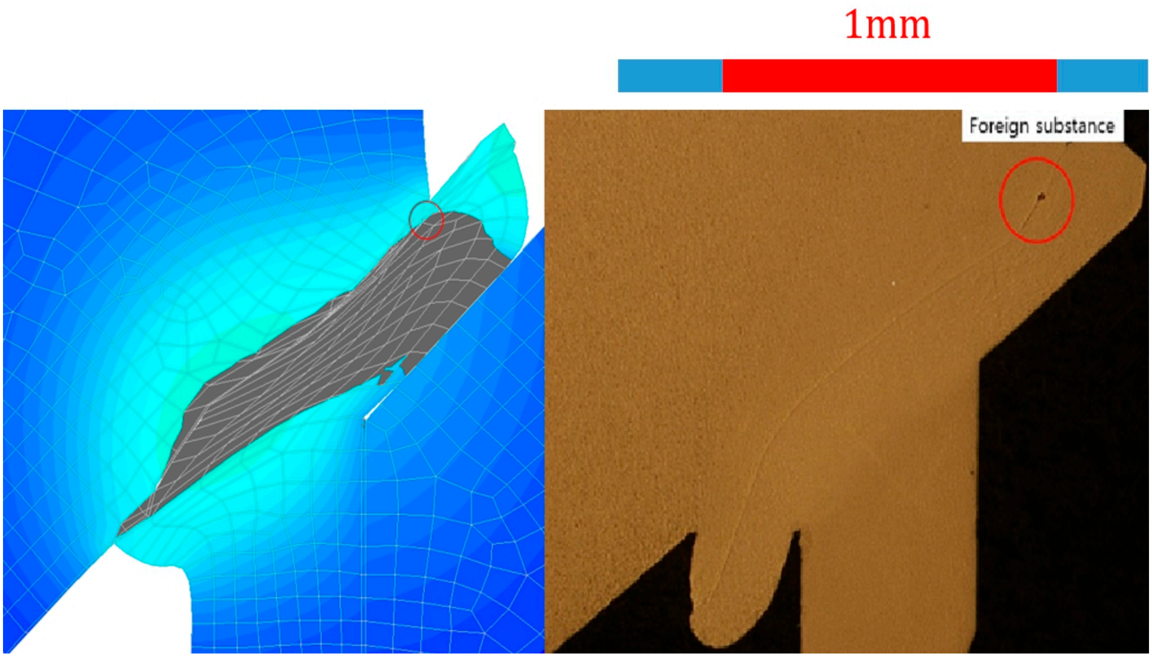

Figure 9. Macrograph (cross-section) of weld joint (14 kA).

6. Conclusions

Analysis of the simulation and test results show that most of the foreign substance flow occurs during the first half of the cycle, which corresponds to the electrode displacement. If the heat input is insufficient, a solid weld or incomplete joint may result, leaving the foreign substance inside. If sufficient melting occurs within the weld, the outer weld reinforcement is significantly formed, and the foreign substance is moved out of the weld by the fluid flow. Therefore, it can be considered that the occurrence of melting that exceeds the tube thickness is an important variable in tube-cap welding, and the first half cycle is an important quality factor during welding. The main findings of this study can be summarized as follows:

- It was observed that the tendency of foreign substances to move in the X and Y directions occurred mainly during the first half cycle of the welding time in a one-cycle process, and the amount of displacement increased as the current value increased. In addition, the study showed that an increase in the amount of molten metal resulted in a greater flow of foreign material;
- Regarding the presence of foreign substances in the base material, it was interpreted that the movement occurs mainly during the first half cycle, and if the heat input is insufficient, the welding occurs in a solid state, leaving foreign substances in the tube. Conversely, if sufficient heat is generated to cause sufficient melting in the weld area, a large amount of weld reinforcement will occur on the outside, causing the foreign substance to move out of the tube due to flow. Therefore, it can be said that the first half cycle of the welding time, such as the flow rate during the reflection cycle, is an important factor in ensuring weld quality and a sound weld.

After actual welding, foreign substances are checked through a macrograph test, but it only checks one side of the weld in the circumferential direction, so there is a limit to reproducibility. However, the most important and vulnerable part of the fuel rod is the weld between the end plug and the cladding tube. Substances, as well as carbide-based ceramic materials, may exist in the weld, and it is significant that simulations have derived welding conditions that can remove foreign substances from the thickness of the tube under conditions that do not cause over-welding.

Author Contributions: Writing original draft and analysis, T.N.; Writing—review and editing, T.K. and Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (2021171020001B).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vagi, J.J.; Martine, D.C. *Development of Methods for End Capping PWR Fuel Element*; Battelle Memorial Inst.: Columbus, OH, USA, 1959; pp. 499–506.
2. Vagi, J.J.; Koppenhofer, R.L.; Martine, D.C. Methods for End Capping zirconium-clad Reactor Fuel Pins. *Weld. J.* **1959**, *38*, 78–84.
3. Dave, S. *Welding Skills & Technology*; Glencoe/McGraw-Hill School Pub Co.: Columbus, OH, USA, 1984.
4. Kim, S.S.; Kim, J.H.; Kim, H.K. Evaluation of End Cap Welding Test for a Nuclear Fuel Rod Having External and Internal Tube Structure. In Proceedings of the KWJS, Pyeongchang, Republic of Korea, 5–7 November 2008; pp. 1377–1380.
5. Kim, W.G.; Kim, Y.C.; Lee, W.J. A Study on the Non-Destructive Inspection for End Closure Welding of Nuclear Fuel Elements for Irradiation Test. In Proceedings of the KWJS, Jeju, Republic of Korea, 20–21 May 2004; pp. 302–304.
6. Kim, S.S.; Kim, E.G.; Lee, J.W.; Yang, M.S.; Lee, Y.H. A Study on Zr-4 Laser Welding for Attachment of Bearing Pads of Nuclear Fuel Element. In Proceedings of the KWJS, Seoul, Republic of Korea, 3–4 May 2001; pp. 178–180.
7. Mabrouki, M.; Gonçalves, D.; Pascal, S.; Bertheau, D.; Henaff, G.; Poulon-Quintin, A. Optimization of the Pressure Resistance Welding Process for Nuclear Fuel Cladding Coupling Experimental and Numerical Approaches. *Metals* **2023**, *13*, 291. [CrossRef]
8. Park, J.-Y.; Na, T.-H.; Lee, T.-H.; Lee, J.-H.; Lee, B.-Y.; Kim, J.-S. Effect of applied current on the formation of defect in PWR nuclear fuel rods in resistance pressure welding process. *J. Nucl. Sci. Technol.* **2015**, *52*, 748–757. [CrossRef]
9. Kim, M.J. *Resistance Spot Welding*; Springer: Cham, Switzerland, 1998.
10. *SORPAS2D Version 12 User Manual*; SWANTEC: Kongens Lyngby, Denmark, 2016.
11. Zhang, W. Design and Implementation of Software for Resistance Welding Process Simulations. *J. Mater. Manuf.* **2004**, *112*, 556–564.
12. Nielsen, C.V.; Zhang, W.; Alves, L.M.; Bay, N.; Martins, P.A.F. *Modeling of Thermo-Electro-Mechanical Manufacturing Processes with Applications in Metal Forming and Resistance Welding*; Springer Science & Business Media: Berlin, Germany, 2012.
13. Nielsen, C.V.; Martins, P.A.F.; Zhang, W.; Bay, N.O. Numerical Method in Simulation of Resistance Welding. In Proceedings of the 6th International Conference on Coupled Problems in Science and Engineering, Venice, Italy, 18–20 May 2015; pp. 322–333.
14. Nielsen, C.V.; Martins, P.A.F. Finite Element Flow Formation. In *Metal Forming*; Academic Press: Cambridge, MA, USA, 2021; pp. 181–249.
15. Na, T.-H. Simulation-Based Characterization of Tube-Cap Resistance Butt Welding of Nuclear Fuel for Light Water Reactors and Development of Melted-Volume Prediction Models. *Int. J. Precis. Eng. Manuf.* **2023**, 1–9. [CrossRef]
16. Na, T.-H.; Na, S.-J.; Park, Y.-W. A study on characteristics of end plug resistance welding process in nuclear fuel rods by experiment and numerical simulation. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 2241–2255. [CrossRef]
17. Na, T.-H.; Na, S.-J.; Ko, M.-H.; Hwang, D.-S. Algorithm development for quality monitoring on end plug resistance weldment of nuclear fuel rods. *Int. J. Adv. Manuf. Technol.* **2017**, *85*, 991–1006. [CrossRef]
18. Na, T.-H.; Lee, B.-H.; Kim, M.-W.; Na, S.-J. Quality monitoring of end plug resistance weldment for nuclear fuel rods by electrode displacement. *Int. J. Adv. Manuf. Technol.* **2017**, *99*, 2509–2522. [CrossRef]
19. Peter, R.; Alfred, S.; Friedrich, G. *Welding of Zirconium Alloys*; A A.N.T. International: Skultuna, Sweden, 2007.