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Process Management Development for Quality Monitoring on Resistance Weldment of Nuclear Fuel Rods

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1. Introduction

Nuclear fuel rods used in nuclear energy are produced by inserting UO_2 pellets, a spring, and injecting helium gas into a zirconium alloy cladding tube. Then, end plugs are resistance welded on each end and the weldment must be durable and reliable because the welded area has the highest risk of leakage within the reactor during irradiation. For quality analysis, burst tests and metallographic tests are performed via sampling. Also, the current, welding force, and displacement are displayed on the indicator during welding. However, real-time quality control is not performed. Due to the importance of fuel rod weldment, many studies on welding procedures have been conducted. However, there are not enough studies regarding weldment quality evaluation. On the other hand, there are continuous studies on the monitoring and control of welding phenomena. In resistance welding, which is performed in a very short time, it is important to find the process parameters that well represent the weld zone formation and the welding process.

In his study, Gould attempted to analyze melt zone formation using the finite difference method[1]. Using the artificial neural network, Javed and Sanders, Messler Jr et al., Cho and Rhee, Li and Gong et al. estimated the size of the melt zone by mapping a non-linear functional relation between the weldment and the electrode head movement, which is a typical welding process parameter[2-6]. Applications of the artificial intelligence method include fuzzy control using electrode displacement, fuzzy control using the optimal power curve, neural network control using the dynamic resistance curve, fuzzy adaptive control using the optimal electrode curve, etc.

Therefore, this study induced quality factors for the real-time quality control of nuclear fuel rod end plug weldment using instantaneous dynamic resistance (IDR), which incorporates the instantaneous value of secondary current and voltage of the transformer, and using instantaneous dynamic force (IDF), obtained real-time during welding. Resistance welding for nuclear fuel rod end plug welding is performed in a very short time (1 cycle = 16.67 m sec). Therefore, it is difficult to observe the variation using general average dynamic resistance (ADR) (approx. 1 – 3 kHz). Hence the patterns of instantaneous dynamic resistance (IDR) and instantaneous dynamic force (IDF) were measured using a measurement frequency of 50 kHz.

2. Material and Methods

This study used Zirconium alloy, which is commonly used as the cladding material for nuclear fuel rods. Zircaloy -4 and ZIRLO are a Zr-based alloy composed of Sn, Fe, Cr, etc. The cladding tube (CT) used for this study was 9.5 mm in diameter, 0.6 mm thick, and the end part of the cladding tube that meets the end plug (EP) was chamfered for improved weldability. A spring was inserted in the cladding tube to increase the packing factor of the nuclear fuel, and the tube was welded. Fig.1 shows the welding diagram.

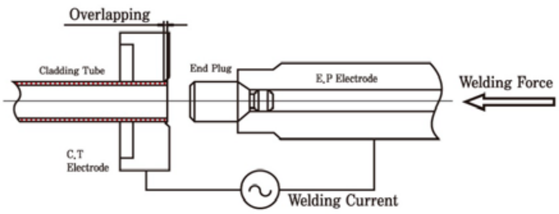


Fig. 1 Welding diagram of sheath and end plug

The welding machine used in this experiment was a single phase alternating current resistance welder with a MIYACHI transformer. To observe the welding characteristics in accordance with the welding conditions, specimens were welded with a welding time of 1 cycle, increasing the current until severe expulsion occurred in the shear rupture area. Measurements were made while increasing the welding forces to 2000 N, 3000 N, and 4500 N. The experiments were conducted under the following conditions; oxidized electrode, increased electrode hole diameter, damaged electrode transport lever, and damaged insulator connecting the electrode. During welding, the current, voltage, and welding force were measured using a resistance monitoring system (WEM-3000, Monitech) with a measuring sampling of 50kHz, and waveforms were observed using a Weld Good Wave program (Monitech).

3. Results and Discussion

3.1 Instantaneous dynamic resistance and instantaneous dynamic Force

Average dynamic resistance (ADR) is a well-known term, expressing the ratio between the effective voltage per half-cycle (I_{RMS}) and the effective current per half-cycle (V_{RMS}), as per Ohm's law. Instantaneous dynamic resistance (IDR) is the instantaneous resistance value resulting from the instantaneous value of current calculated from the corresponding instantaneous voltage at the same time, using Ohm's law. The equation is expressed below.

$$IDR_i = \frac{Voltage\ of\ instantaneous\ value\ (V_i)}{Current\ of\ instantaneous\ value\ (I_i)},\Omega\ -----(1)$$

Fig.2 shows a conceptual diagram of ADR and IDR regarding the measured current and voltage. ADR is consisted of only one raw datum, whereas IDR is consisted of approximately 400 pieces of data based on a measurement frequency of 50 kHz. Therefore, it is easy to identify the tendency of the pattern. The measured current and voltage showed a sine wave. On the other hand, IDR showed a decline and decreasing pattern, as shown in Fig 2. It is considered that although the resistance is high due to high contact resistance during the initial stage, the resistance decreases with a negative angle due to increased contact area caused by increasing current. It is considered that the resistance increased again at the beginning the second half-cycle because the contact resistance increased as the weldment was cooled and the current flowed again.

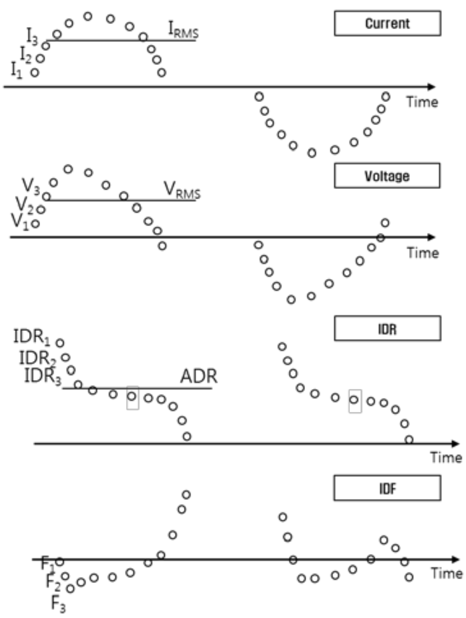


Fig. 2 Conceptual diagram of IDR and IDF

According to Ma et al., electrode force indicates welding status and can be used as a signature for monitoring weld quality[7]. However, the drawback is that the transducer, in general, is more complicated and more vulnerable to contamination caused by electromagnetic force, when compared to the dynamic resistance or electrode displacement methods.

In the case of butt welding, however, it is considered to be an important factor that can assess overlapping phenomena, etc. Therefore, quality was assessed using the instantaneous value of the welding force, not the average value of the welding force, during welding. Instantaneous Dynamic Force (IDF) refers to the real-time welding force during welding. The equation is presented below.

$$IDF_j = Force\ of\ instaneous\ value\ (F_j), N\ \ -----(2)$$

A welding force sensor was placed behind the end plug (EP) and was attached on an insulated part to prevent the current from flowing.

3.2 Analysis on IDR and IDF waveform pattern with increasing current

The variation of IDR in accordance with increasing current is shown in Fig.3. The time required for the IDR value to reach "0" mΩ took longer as current increased. The angle of decline decreased as the current increased.

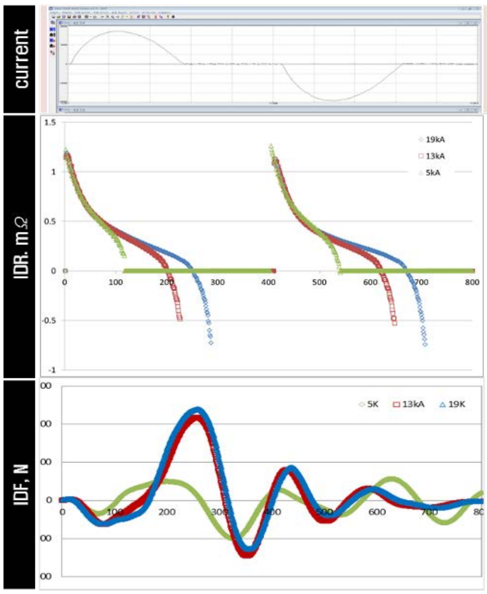
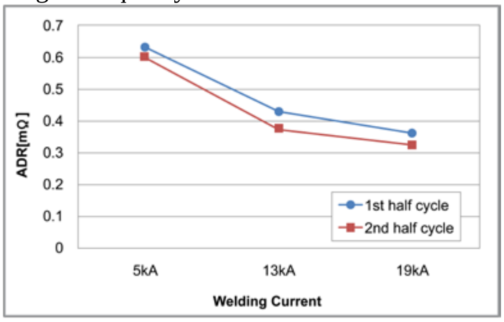
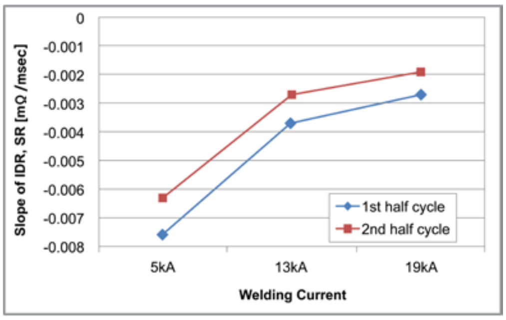


Fig. 3 IDR and IDF waveform with increasing current

Fig. 4 shows that the ADR per half-cycle decreases and the slope of instantaneous dynamic resistance (SR) flattens as the current increases. Since the welding machine's, output pattern characteristics increase every half-cycle, it was observed that the ADR of the first half-cycle was lower than that of the second half-cycle, and the angle of SR flattened. Therefore, it was determined that SR is an important parameter in assessing weld quality.



(a) Average dynamic resistance (ADR)



(b) Slope of instantaneous dynamic resistance (SR)

Fig. 4 ADR and SR per half-cycle with increasing current

Fig. 3 shows IDF waveform in accordance with increasing current. At 5 kA, where cold welding occurs, the IDF pattern values were lower than those of other patterns, and as current increased, the slope of instantaneous dynamic force (SF) shifted right. Therefore, it was determined that SF is also an important parameter in assessing weld quality.

3.3 Analysis on IDR and IDF in accordance with electrode contamination

The experiment on electrode contamination was conducted by oxidizing the electrode with a torch. Fig. 5 shows the IDR pattern when using an oxidized electrode. In the first half-cycle, the initial IDR value was lower than the welding current waveform of 13 kA in Fig. 3 and showed an irregular curve at the slope section. It was determined that this phenomenon was due to the oxidized electrode causing irregular heat flow.

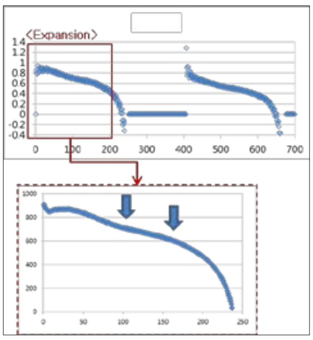
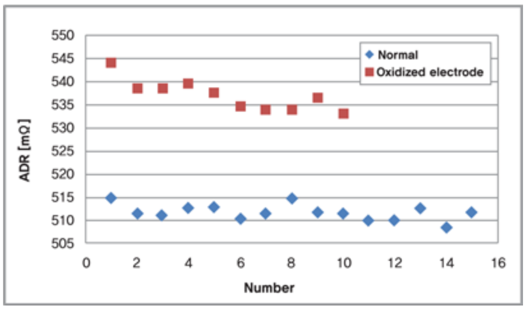
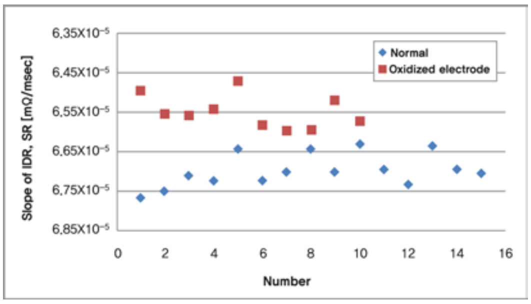


Fig. 5 IDR pattern when using oxidized electrode

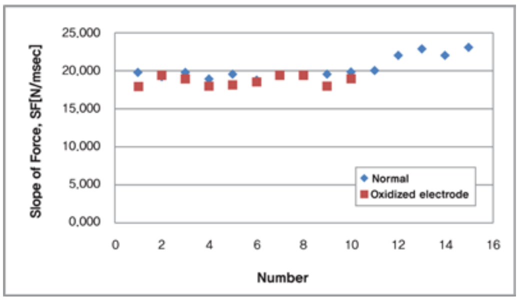
Fig. 6 shows SR and SF values when using a normal electrode and an oxidized electrode. ADR was high when using an oxidized electrode because the oxidized electrode disturbed current flow, and decreased the current. SF did not differ, but SR increased.



(a) Average dynamic resistance



(b) Slope of instantaneous dynamic resistance



(c) Slope of instantaneous dynamic force

Fig. 6 Parameter analysis when using oxidized electrode

4. Conclusions

From this experiment for quality monitoring on the end plug resistance weldment of PWR nuclear fuel rods, the main results can be concluded as below.

1) Since the end plug resistance weldment of nuclear fuel rods has a fast welding speed of 1 cycle, it was determined that increasing the measuring frequency and using instantaneous dynamic resistance (IDR) and instantaneous dynamic force (IDF) per half-cycle are desirable.

2) As current increased, average dynamic resistance (ADR) decreased, but the slope of instantaneous dynamic resistance (SR) increased.

3) Depending on the level of electrode contamination, it was impossible to evaluate a tendency from the current and slope of instantaneous dynamic force, but it was

possible from the slopes of average dynamic resistance and instantaneous dynamic resistance.

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