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Characterization of Microstructure and Mechanical Properties of Zirconium Alloy Welds in PHWR Fuel Rods

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1. Introduction

The dislodgment of a fuel rod from a bundle of spent fuel rods during underwater transfer to a dry storage container due to irradiation damage and embrittlement of the welds between the end plate and end cap is a concerning event in the nuclear industry. The welding part of a heavy water nuclear fuel bundle comprises of 37 fuel rods welded to an endplate, with spacers and supports brazed to the surface. In this study, we aim to investigate the microstructure and mechanical properties of the welding part of nuclear fuel rods for heavy water reactors. We will examine any potential issues with the welding of the nuclear fuel end plate and end cap and evaluate changes in microstructure and mechanical properties due to irradiation with hydrogen and ions in the zirconium alloy welding part. The findings of this research may help prevent future dislodgment of fuel rods from spent fuel bundles, thereby enhancing the safety of nuclear facilities.

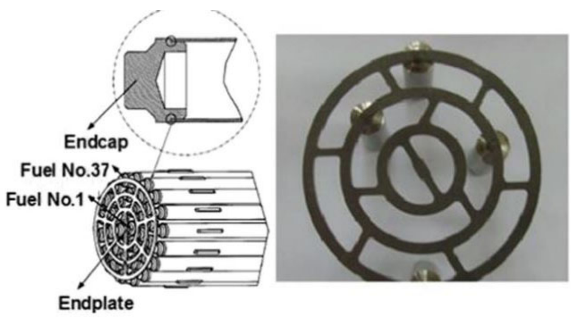

Fig. 1. Schematic diagram and photograph of nuclear fuel rods used in PHWR.

2. Experimental and Results

A cutter was used to make a vertical cut at the area where the rod end cap and end plate were welded. The cross section was polished using 200 and 120 µm grit sandpaper, followed by further polishing with diamond suspension up to 3 and 1 µm. Subsequently, the surface was finely polished with colloidal silica and subjected to 20 V, 10 s electrolytic polishing using 900 mL methanol + 100 mL perchloric acid and the Selectropol equipment (as depicted in Fig 2(a)). An optical microscope (OM) was used to observe and analyze the sample's surface. Photographs taken with the OM were connected and are shown in Fig 2(b).

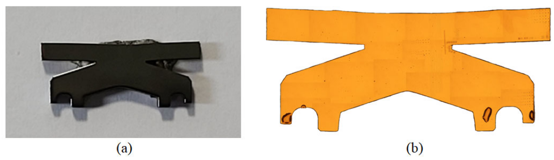

Fig. 2. (a) A cross-sectional specimen taken from a weld between an end plate and end cap made of Zr alloy, (b) a photograph of the specimen taken with an optical microscope (OM)

A Bercovich nano indentation tip was used to perform an indent on the cross section, with a load of 100mN at 40 nm intervals, covering a large area.

The secondary-electron (SE), Inverse Pole Figure (IPF), and Kernel Average Misorientation (KAM) maps of the cross section are shown in Fig. 3. he IPF map depicted in Fig. 3 confirms that the microstructure of the end plate had been subjected to rolling, with the presence of an elongated grain structure. The end cap exhibited a spherical grain structure with a random orientation, as shown in Fig. 3. In the welded region, the grain size was small, and the shape was difficult to determine. The KAM measurement, shown in Fig. 3, indicated a high degree of misorientation in the welded section, suggesting that significant residual stress had accumulated during welding.

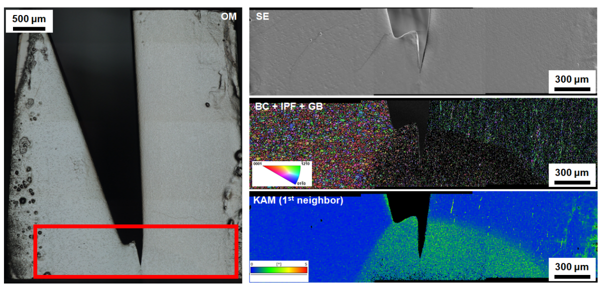

Fig. 3. Zr-alloy cross section (OM, SE, IPF, KAM map)

A nano indentation graph based on EBSD data is shown in Fig 4. The indentation test was performed from the upper part of the end plate to the lower part of the end cap, with a load of 100 mN. The tests were for 10 times, from top to bottom, to obtain an average value and deviation. The top of the end plate, which was identified by the rolled structure, exhibited a hardness value of approximately 3 GPa, with a small deviation, as shown in Fig. 4. In contrast, the lower end plate, which was significantly affected by welding, showed a higher hardness value of approximately 3.5 GPa or more. In the case of the end cap, the deviation of the hardness value was large, unlike the end plate. This variation may be influenced by the random distribution of orientations, as shown in the Inverse Pole Figure (IPF) Map of the Electron Backscatter Diffraction (EBSD) data. Zr has a Hexagonal Close-Packed (HCP) crystal structure, which exhibits anisotropic physical properties. Therefore, the hardness value varies depending on the orientation.

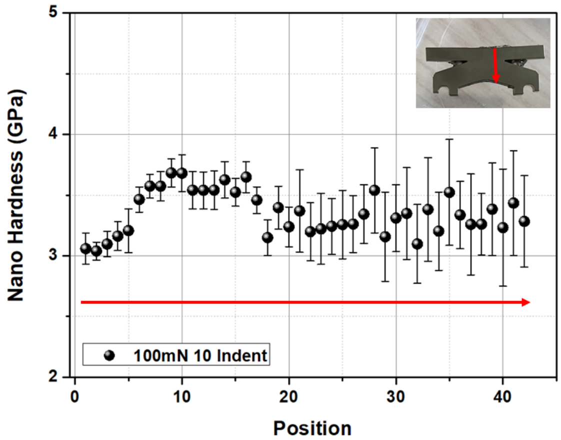

Fig. 4. A graph of nano hardness measurements obtained by nano indentation at different locations.

To investigate the size effects of nanoindentation in the end plate and end cap, we performed ten indents at random positions for each force between 5 mN to 800 mN. The resulting graph is shown in Fig. 5, which demonstrates the so-called "smaller is stronger" size effects for both materials. Notably, the end plate area showed lower hardness values and deviations than the end cap area, where the end cap exhibited relatively higher hardness values and deviations. These differences were observed regardless of the applied force and were found to be correlated with crystal orientation, as confirmed by the IPF Map obtained from EBSD analysis.

3. Conclusions

This research measured mechanical properties by manufacturing a specimen based on damage in the Zr-alloy welded part between the end plate of the nuclear fuel rod and the end cap. The end plate showed elongated grains with a relatively low hardness value of 3 GPa. On the other hand, the end cap showed spherical grains with a high deviation in hardness, which was attributed to the crystal structure of Zr. The welding area showed a relatively high hardness value and residual stress, as confirmed by EBSD's KAM result value. To minimize welding part breakage during movement and storage of nuclear fuel rods, additional experiments are required to alter the mechanical properties of the welding area. Future research plans include examining changes in mechanical properties when exposed to ions and hydrogen and mapping hardness values in large areas to identify spatial distributions.

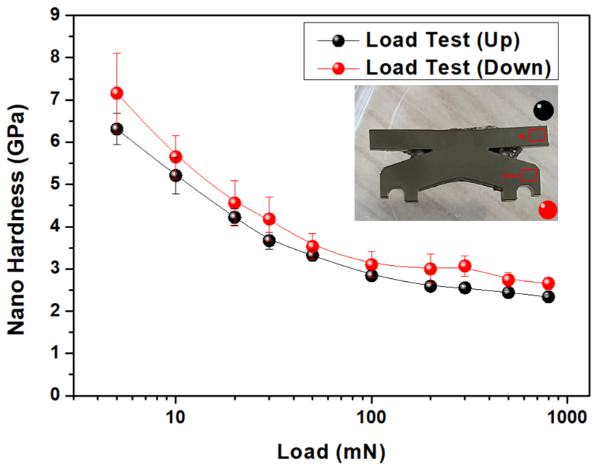

Fig. 5. The hardness values for the end plate and end cap areas with minimal weld impact, measured using a range of forces at different scales.

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