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Consideration of Weld Mechanical Properties on the Structural Performance of Nuclear Components

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1. Introduction

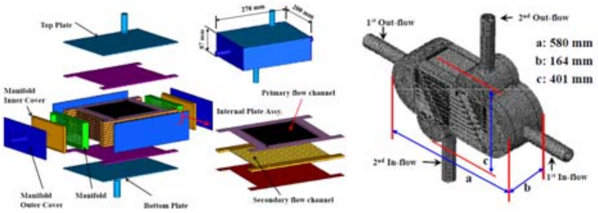
Microstructures in a weld zone, including the weld and heat affected zone (HAZ), are different from that in a base material. Consequently, the mechanical properties in the weld zone are different from those in the base material to a certain degree owing to different microstructures and residual welding stresses. When a welded structure is loaded, the mechanical behavior of the welded structure might be different from the case of a structure with homogeneous mechanical properties.

In this study, to investigate the effect of the weld material properties on the mechanical behavior of welded nuclear components, such as a plate-type process heat exchanger (PHE) prototype made of Hastelloy-X, a printed circuit heat exchanger (PCHE) prototype made of SUS316L for a very high temperature reactor, and a spacer grid assembly made of Zircaloy-4 for a PWR fuel assembly, the structural strength analysis and evaluation are performed considering the weld mechanical properties [1, 2] recently obtained by an instrumented indentation technique, and the analysis results were compared with the results of the previous research [3, 4] using the base material properties.

2. Nuclear Components

Fig. 1 shows the overall dimensions and each part of the lab-scale PHE and PCHE prototypes, which were designed for high-temperature performance test at KAERI. The flow plates for the primary and secondary coolants were stacked in turn, and bonded along the edge of the flow plate using a solid-state diffusion bonding method. After stacking and bonding the flow plates, the outside of the lab-scale PHE and PCHE prototypes was covered with plates and welded along its edges using TIG welding.

Fig. 2 shows the Zircaloy spacer grid assembly of a PWR fuel and a weld bead at the intersections of the straps. Spot welding by a laser beam welding technique is prevalent in most of the Zircaloy spacer grid assembly manufacturing vendors, for the purpose of a smaller bead size and a larger weld penetration at the welding parts. The diameter of the weld bead is about 2 *mm* and the width of the HAZ is just below 1 *mm* for a Zircaloy spacer grid strip 0.457 *mm* thick.



a) PHE prototype b) PCHE prototype

Fig. 1 Lab-scale PHE and PCHE prototypes

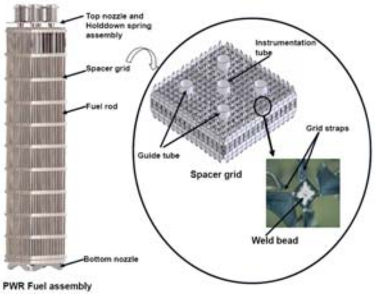


Fig. 2 PWR fuel assembly and spacer grid

3. Measurement of Weld Properties

An instrumented indentation method is known to be a remarkably flexible mechanical test to obtain the mechanical properties with minimal specimen preparation [5] by continuously measuring the load and depth if an indentation is made. An additional advantage of the indentation is the ability to obtain the mechanical properties in a narrow or inaccessible region through other methods such as uni-axial tension or a compression test.

Based on the measured data using an instrumented indention method, the normalized mechanical properties in the base material, the weld, and the HAZ were obtained.

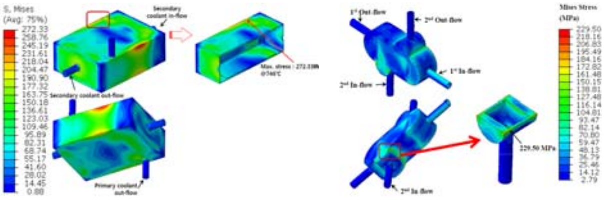
4. Finite Element (FE) Modeling and Analysis

FE modeling and analyses were carried out on the lab-scale PHE and PCHE prototypes. For the sake of simplicity and an understanding of the overall mechanical behavior of the lab-scale prototypes, the FE models are composed of 3-D linear solid elements including tetrahedron elements. The weld zones of the lab-scale PHE prototypes are modeled, where the weld beads along the edges and HAZ are represented. Based on the thermal analysis results and the imposing structural boundary conditions considering the pipeline stiffness of the gas loop at KAERI, structural analyses were carried out on the lab-scale prototypes using ABAQUS Ver. 6.8.

An FE model for predicting the crush strength of the sub-size spacer grid (7x7 array) has been established, reflecting a real test environment. The 4-node shell elements were used for the inner/outer straps. Since the slot width in the inner straps is wider than the inner strap thickness, there may be a gap at the interconnected parts. Thus, surface-to-node contact elements were used at these interconnected parts to simulate the gap conditions. The FE model is composed of 24,448 2-D linear quadrilateral shell elements. Crush strength analyses are carried out using a commercial FE code LS-DYNA.

5. Results

Fig. 3 show the elastic stress contours at the pressure boundary of the lab-scale prototypes. For the PHE prototype, the maximum local stress of 272.33 MPa around the edge between the top plate and side plate exceeds the yield stress of Hastelloy-X (239.70 MPa at 746℃) by 13.61%. On the other hand, the degree of exceeded yield stress in the weld is decreased for the analysis using the weld material properties. For the PHE prototype, the maximum stress of 272.33 MPa exceeds the yield stress of the weld material (269.50 MPa at 746℃) by only 1.05%. Thus, a smaller degree of excess yield stress is attributed to a larger yield stress of the weld material than the base material.



a) PHE prototype b) PCHE prototype

Fig. 3 Stress contours of lab-scale prototypes

For the PCHE prototype, the maximum local stress was about 229.5 MPa, which exceeds the yield stress of 117.1 MPa. The maximum local stress of 229.5 MPa is equivalent to a Tresca stress of 221.8 MPa. When evaluating the maximum local stress according to ASME Sec. III T-1300, NB-3222, the maximum Tresca stress of 221.8 MPa is far below the allowable stress limit ($3S_m$) of 283.3 MPa when considering the peak stress. Meanwhile, it was found that the mechanical properties, such as the yield stress, in a weld zone are a little lower than those of the base material. When considering the mechanical properties in the weld zone, the maximum Tresca stress of 221.8 MPa is far below the allowable stress limit of 263.2 MPa in the weld zone ($3S_m$).

Fig. 4 shows the results of crush strength analyses on the three kinds of FE model for using the base material properties and weld properties. According to Fig. 4, a crush load increases and becomes saturated to maximum values as the impact velocity increases, and the maximum crush loads using the weld material properties for three FE models are about 30 % lower than those using the base material properties. Consequently, for a more reliable crush strength analysis on the Zircaloy spacer grid, an FE analysis considering the weld material properties is necessary instead of an FE analysis using the base material properties.

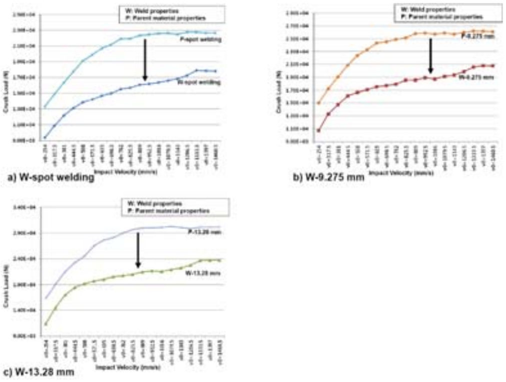


Fig. 4 Crush load vs. impact velocity

6. Summary

1. High-temperature elastic structural analyses on the lab-scale PHE and PCHE prototypes were performed. Even though the maximum stress exceeds the yield stress in the weld zone, the degree of excess in the yield stress may be different owing to the different yield stresses in the weld zone.
2. The maximum crush loads of a PWR spacer grid using the weld material properties are about 30% lower than those using the base material properties.
3. For a more reliable strength analysis on the welded nuclear components, an FE analysis considering the weld material properties seems to be necessary.

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