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Thermal fatigue testing on simulated specimens

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1. Introduction

Systems, structures, and components (SSCs) in nuclear power plants (NPPs) are subjected to cyclic thermal and mechanical loads during operation. Therefore, SSCs are designed to have a sufficient margin against fatigue damage in accordance with design codes [1]. However, the fatigue design of SSCs has required additional consideration of the environmental effects on the fatigue life of metals, which reduces the fatigue design margin. To address this, the efforts have been made to develop new fatigue assessment methodologies and procedures with realistic conservatism and advanced analytical methods [2-4]. However, test data simulating thermal fatigue phenomena under operational conditions are not sufficient to develop and validate new assessment methods and procedures.

Therefore, this study developed a thermal fatigue test system capable of applying thermal and thermo-mechanical cyclic loads and performed fatigue tests using specimens simulating the nozzle and pipe connection. From the results, the crack initiation site and patterns and cycles to failure were investigated at different loading conditions.

2. Experiments

2.1 Test System and Specimen

Figure 1 shows a schematic diagram of the fatigue testing system used in the test [5]. As shown in Fig. 1, the outer surface of the specimen was continuously heated while the inner surface was periodically cooled with coolant. The specimen was subjected to a cyclic thermal stress induced by a periodic change in the temperature gradient within the wall. In addition to the thermal stress, a cyclic axial stress could be applied to the specimen by restraining the axial displacement during heating/cooling. A constant axial stress could also be applied by the application of a dead weight load.

Figure 2 illustrates the specimen used for the tests. The specimen has different outside diameters and thicknesses to simulate the geometry of the nozzle and pipe connection, and includes a notch to see the stress concentration effect. The specimen was made of SA182 F316L stainless steel, which is commonly used as a structural material for NPPs.

2.2 Test Conditions and Procedures

Three types of loading conditions were considered in the test: thermal loading without external load (i.e., free condition), thermal loading with cyclic axial load induced by restraining axial displacement (i.e., fixed condition), and thermal loading with constant axial load by dead weight (i.e., constant load condition). Regardless of the loading conditions, the specimen was heated to a temperature of 350℃ and cooled by flowing water at 20℃ for 5 seconds. After cooling, the specimen was dried by blowing high-pressure air through it for 8 seconds and reheated to 350℃. The reheating interval was 58 seconds.

For all of the tests, the axial load, displacement, and temperatures were measured and recorded at a rate of data per second. Load was measured using a load cell mounted on the lower fixture, and temperatures were measured at various axial locations on the specimen surface and at the inlet and outlet of the coolant. Displacement was measured using a linear variable displacement transducer (LVDT) mounted on both the upper and lower fixtures. Periodically, the test was stopped and the inner surface of the specimen was visually inspected with an endoscope to determine the location and pattern of crack initiation and the number of cycles to failure.

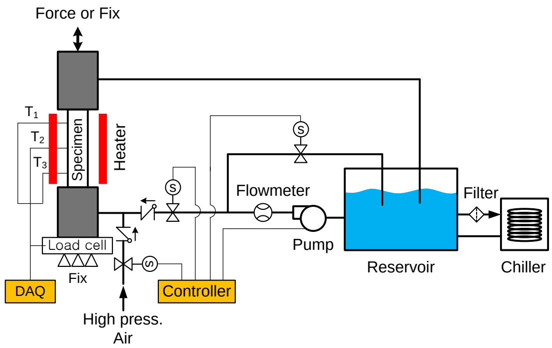

Fig. 1. Schematic Diagram of tests system

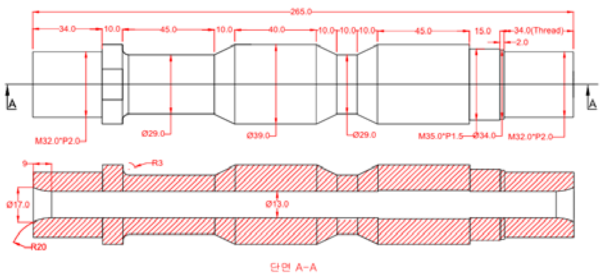

Fig. 2. Simulated specimen shape for thermal fatigue testing

3. Results and Conclusions

Figure 3 shows the temperature distribution measured on the surface of the specimen during heating and cooling. It can be seen that the specimen was uniformly heated to 350℃ during heating, although the temperature varied during cooling due to the difference in specimen thickness.

Irrespective of the loading conditions, small indications were observed on the inner surface at 10,000 cycles, which were not observed at 7,500 cycles. In the free and fixed conditions, all the indications were initiated in the thick-section and in the axial direction. In the constant load condition, the indications were observed not only in the thick-section but also in the notched section. The indications in the notched section were in the circumferential direction. As the number of cycles increased, the number of indications increased and the shapes became more distinct. However, the indications did not grow and penetrate the specimen wall until 20,000 cycles for all loading conditions.

Acknowledgements

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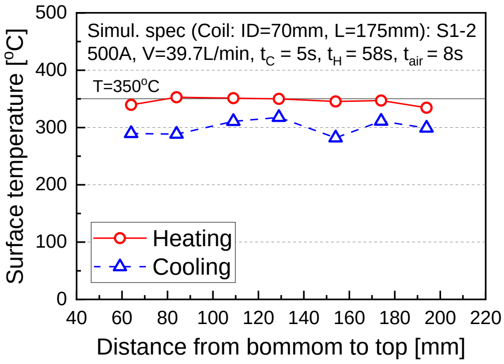
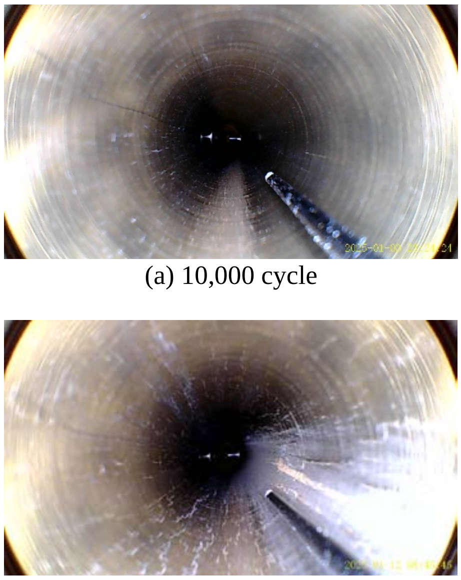


Fig. 3. Thermal fatigue during heating and cooling temperature distribution at the specimen surface



(a) 10,000 cycle

(b) 20,000 cycle

Fig. 4. Inner surface of the specimen under free condition