Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Creep Tests of P91 Elbow Pipe by Induction Bending Technology

Jong-Bum Kim[a*], Chang-Gyu Park[a], Tae-Won Na[a], Junehyung Kim[a]
[a]*Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Deajeon, Korea*
**Corresponding Author : jbkim@kaeri.re.kr*

1. Introduction

The Mod.9Cr-1Mo (P91) steel is an advanced material to be applied for the high temperature structures of Gen-IV reactors such as a Sodium-cooled Fast Reactor. It is a registered material in ASME B&PV Code, Section III, Division 5 [1].

The potential sodium leakage in P91 piping of SFR can be reduced by adopting induction bending technology instead of the conventional welding manufacturing method, which can minimize the number of welds in the piping layout, including elbows. Prior to the application of this new methodology, tensile tests, impact tests, and hardness tests were conducted on P91 piping before and after the induction bending process to evaluate the applicability of this technology[2]. Also, T.W. Na[3, 4] evaluated material properties by performing mechanical tests at high temperatures and confirmed the applicability of bending processes by verifying that they meet ASME Code requirements.

In this study, after conducting material tests, creep tests were performed on induction bent elbow pipe to further verify the applicability by confirming that the pipe maintains structural integrity.

2. Creep Tests

Fig. 1 shows the induction bent elbow pipe made of P91 steel of which chemical composition is shown in Table 1. Outer diameter and thickness of an elbow pipe are 219.1 mm and 8.18 mm, respectively and a curvature radius is 2DR (406.4 mm). To facilitate the use of the induction bent elbow pipe in conjunction with the large-scale structural test machine shown in Fig. 2 of which capacity is 25 tons, flange was welded onto the lower portion of the elbow pipe to create an integral part. This allowed the test model to be easily installed on the testing equipment as shown in Fig. 2. To apply test load to the test model through pin, a 50 mm hole was machined at the upper straight portion end of the elbow pipe. Pin were inserted into this hole to enable the application of load to the test model.

To perform the creep test on the test model, the 20 tons capacity structural test rig was prepared. Fig. 2(left) shows the schematic of thes rig and Fig. 2(right) shows the actual structural test rig. The setup consists of a main frame with hydraulic pistons applying loads to test model, hydraulic control units generating and controlling the pressure, load cells and load indicators for measuring forces applied to the piping model.

The elbow pipe is secured to the test machine's frame using a holder jig and pin is used to apply loads directly to the elbow pipe. Then the dampers made of springs that absorb small displacements to reduce fluctuating loads are installed.

The special heating device that provides a high-temperature environment of 550°C is prepared and installed inside the elbow pipe, so that it does not come into contact with the curved part of the pipe, and thermocouples are installed on the curved part to control the temperature of the elbow pipe.

The loading on the piping in SFR is not just due to primary loads such as pressure and dead weight, but also due to secondary loads like anchor displacement movement. Therefore, in order to investigate the creep behaviors properly that may occur in the pipe systems at high temperatures, we conducted two types of pipe creep tests: one for primary loading conditions and another for secondary loading conditions.

In this study, two types of creep tests were conducted. The first type (CREEP1) is a standard creep test where the pipe is subjected to constant load at 550℃ and the increase in creep deformation over time was measured. The second type (CREEP2) involves applying a constant displacement load to the pipe at 550℃ and how the internal resistance force relax with respect to time was investigated.

Table 1. Chemical compositions of the P91 steels (wt.%)

C	Si	Mn	S	P	Cr	Mo	V	Nb	Al	Ni	N
0.1	0.41	0.4	0.001	0.013	8.49	0.94	0.21	0.08	0.01	0.1	0.06

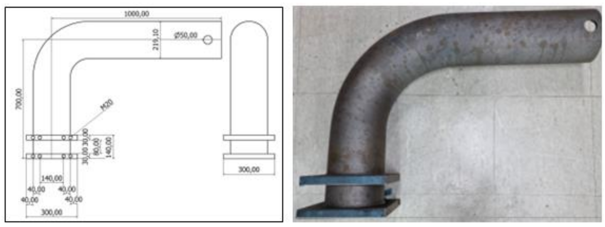

Fig. 1 Induction Bent Elbow Pipe

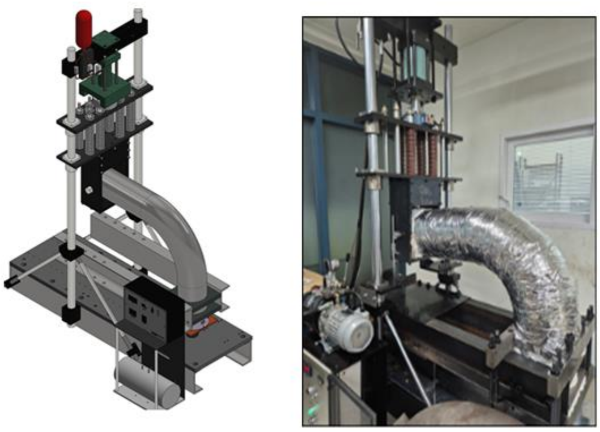

Fig. 2 Creep Test Rig

CREEP1 Test

The high temperature constant-load creep test (CREEP1) of the elbow pipe was performed by applying a constant load to the test model in its closed direction at 550°C. After starting the heating, the target temperature of 550°C was reached approximately 1.5 hours and after maintaining this condition for 2 hours to achieve a stable state, the load was applied to the elbow pipe. Using a hydraulic device, the load was increased up to 7,340 Kgf (72 kN), and the displacement was measured. In CREEP1 test, the load increase process was carried out in nine stages accounting for the condition of the test rig. And then, the load of 72 kN was maintained at 550°C while measuring the displacement. The results of the CREEP1 test are shown numerically in terms of creep displacement over time on the left side of Fig. 3, and diagrammatically on the right side of Fig. 3.

시간(분)	변형량(mm)	시간(분)	변형량(mm)
0	0	135	36.1
5	5	145	37.8
10	7.5	155	39.5
15	10	165	41.1
20	12	176	43
25	13.5	185	44.2
30	15	195	45.7
35	16.5	205	47.2
40	17.5	215	48.8
45	18.5	225	50.3
55	20.7	235	51.8
65	23	245	53.4
75	25	255	54.8
89	28	265	56.3
95	29	275	57.9
105	30.8	285	59.3
118	33.5	295	60.8
125	34.5		

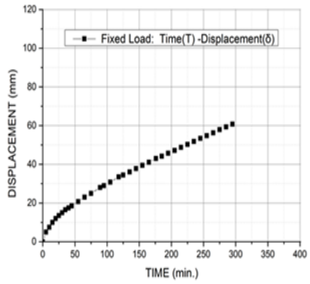

Fig. 3 Creep Displacement from CREEP1 Test

For the elbow pipe subjected to a constant load of 72 kN, the creep displacement exceeded 60 mm within 295 minutes (approximately 5 hours), and the test was stopped. As can be observed from Fig. 3, typical primary creep behavior appeared during the initial 1 hour and secondary creep behavior thereafter, where the creep strain rate remained almost constant. Over the period of 295 minutes, the creep displacement measured at the end of the elbow pipe was found to be 60.8 mm.

After the CREEP1 test was completed, the test model was disassembled and the thermal insulation was removed. The resulting appearance is shown in Fig. 4(left), where large displacement can be visually observed. The large displacement at the load point of the test model indicates that a substantial amount of deformation occurred due to high stresses acting on the elbow section. This is depicted in Fig. 4(right). The longitudinal diameter and transverse diameter of the deformed elbow, measured using a caliper gauge, were found to be 202.0 mm and 237.3 mm, respectively.

Fig. 4 Test Model after CREEP1 Test

Compared with the design piping outer diameter of 219.1 mm, these values represent a reduction of 7.8% and an increase of 8.3%, respectively. Samples from deformed region will be taken for detailed creep damage examination to be conducted subsequently.

CREEP2 Test

The CREEP2 test was conducted on the elbow pipe at 550°C to analyze its creep behavior under constant displacement condition, utilizing the same testing equipment used for the CREEP1 experiment. While the hydraulic system was used to apply a constant load in CREEP1 test, the hydraulic system was replaced with a mechanical screw jack to effectively maintain constant displacement in the CREEP2 test. The use of hydraulics poses limitations for maintaining displacement over long periods since slight oil leakage within the hydraulic cylinder can hinder precise control and is difficult to completely prevent. In contrast, the mechanical screw jack design ensures stable maintenance of displacement, provided that it remains stationary. To further enhance stability during testing, stoppers were installed on the test device column to prevent additional displacements.

The load was gradually increased by adding displacement until it reached 7,340 Kgf (72 kN) and the final value of displacement was 38.9 mm. Following this, the displacement value of 38.9 mm was fixed and maintained for a total duration of 720 hours (approximately one month) while conducting the test.

Fig. 5(left) shows the load relaxation results measured on elbow test model at 550°C with its displacement held constant for one month (720 hours). It is evident that within the initial 5 hours, the load was rapidly reduced from 72 kN to about 52 kN, representing a 27.8% drop. Thereafter, the decrease in load became more gradual. During 720 hours (approximately one month), the load had decreased to 41.2 kN, representing an overall reduction of 42.8%. For convenience, Fig. 5(right) is redrawn as a log plot to better understand the pattern of this load relaxation. From this log plot, it is clear that the decreasing rate in load follows a linear trend. Although due to time constraints, the CREEP2 test was only conducted for 720 hours under constant displacement conditions, this linear pattern on the semi-log scale suggests that further relaxation could be predicted using logarithmic decay assumptions after this period.

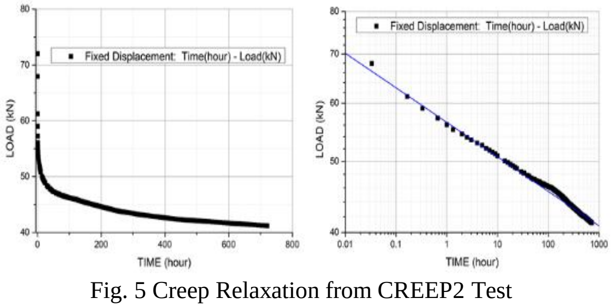

Fig. 5 Creep Relaxation from CREEP2 Test

Therefore, based on these findings, it is inferred that continued load relaxation beyond the 720 hours of test period would follow a predictable and linear trend as indicated by the log plot.

3. Results and Discussion

In this study, we performed a creep test (CREEP1) under constant load of 72 kN and a creep test (CREEP2) under constant displacement of 38.9 mm, and analyzed the results.

While no visible damage such as creep fracture was observed from CREEP1 test, we plan to specifically assess whether and to what extent creep damage has occurred by collecting specimens from high stress region on elbow pipe through metallographic examinations using such as SEM or TEM. In the case of CREEP2 test, the creep strain appeared to be smaller than in CREEP1, indicating that securing structural integrity might be easier. Also, we plan to collect specimens from elbow section in CREEP2 test model and conduct metallographic examinations to check the potential creep damages as well.

The results obtained from this study will serve as useful references for analyzing the high temperature creep behavior of SFR piping structures in the future.

Acknowledgement

We would like to express our sincere gratitude to Professor C.S. Seok of Sungkyunkwan University for invaluable guidance and support throughout this research. This work was supported by a grant from the National Research Foundation of Korea (NRF) funded by the Korean government (Ministry of Science and ICT) (RS-2022-00155157).

REFERENCES

[1] ASME Boiler and Pressure Vessel Code, Section III, Division 5, High Temperature Reactors, 2021.

[2] N.H. Kim, J.B. Kim, S.K. Kim, “Applicability of the induction bending process to the P91 pipe of the PGSFR”, Nuclear Engineering and Technology 53, p1580-1586, 2021.

[3] Tae-Won Na, Nak-.Hyun Kim, Chang-Gyu Park, Jong-Bum Kim, and Il-Kwon Oh, “Validation of applicability of induction bending process to P91 piping of prototype Gen-IV Sodium-Cooled fast Reactor (PGSFR)”, Nuclear Engineering and Technology 55, p3571-3580, 2023.

[4] Tae-Won Na, Nak-Hyun Kim, Chang-Gyu Park, Junehyung Kim, Jong-Bum Kim and Il-Kwon Oh, “Applicability analysis of induction bending process to P91 piping of PGSFR by high-temperature fatigue test”, Nuclear Engineering and Technology 56, p5190-5200, 2024.