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Creep Properties of P91 Induction Bent Pipe for PGSFR

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1. Introduction

Introduction The adoption of induction bending technology in pipe manufacturing for various industrial applications is on the rise. This technology is particularly appealing for nuclear facilities, offering significant reductions in the number of welds required for curved sections like elbows[1-3]. Despite the advantages, its deployment in nuclear plant piping has been limited. This study aims to minimize welding in the P91 pipes of the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) to decrease potential leakage risks. We have evaluated the suitability of induction bent P91 pipes through a series of creep tests at 550°C, examining specimens from P91 pipes shaped by induction bending, to verify if their creep properties meet the rigorous requirements of ASME B&PV Code[4].

2. Experimental Setup and Specimens for Creep Tests

Creep tests were conducted at a consistent temperature of 550°C within a cylindrical furnace, using a dead load method while creep strain measurements were taken via an LVDT connected to the collars by extensometer. The setup is shown in Figure 1. As illustrated in Figure 2, a 90° pipe elbow was crafted through induction bending of a SA335 P91 seamless straight pipe, which measures 559 mm in outer diameter and 12.7 mm in thickness. Due to the challenges of bending pipes with a large D/t ratio to a tight radius, the pipe was bent to a curvature radius of 2.0D. Seven specimens were extracted from the extrados of the bent pipe, each 57 mm in length, as depicted in Figure 2(a). The middle section of each specimen, smooth and cylindrical, has a diameter of 3 mm and a length of 15 mm. Both ends of these specimens were threaded for M6 bolts attachment. Collars were designed at 24 mm intervals on each end of the smooth section to attach an extensometer, as depicted in Figure 2(b).

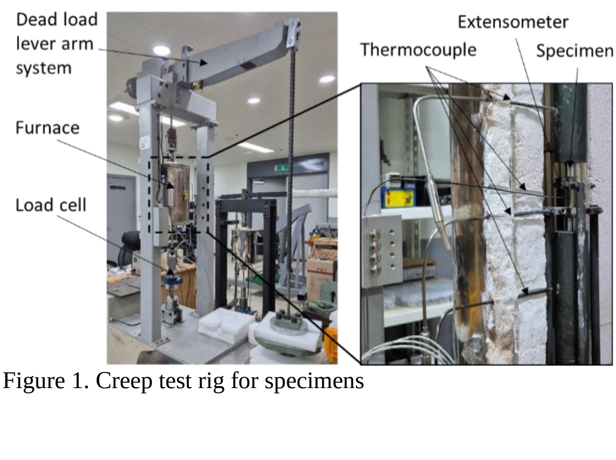

Figure 1. Creep test rig for specimens

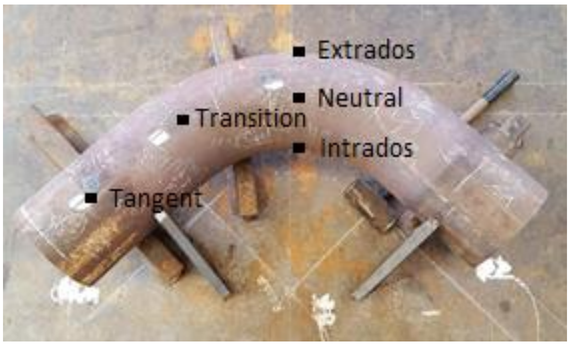

Figure 2. P91 induction bent pipe for specimen fabrication

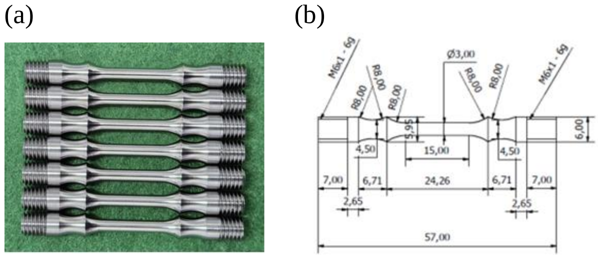

Figure 3. (a) Fabricated specimens for creep tests, (b) drawing of the specimen

3. Creep Tests

Creep testing was conducted with the test temperature maintained at 550°C. The seven specimens were subjected to tensile stresses ranging from 240 MPa to 360 MPa by applying dead loads. Throughout the testing process, specimen temperatures were monitored, and displacement data were recorded via LVDT signals. The tests continued until specimen rupture occurred. The appearances of the seven tested specimens post-testing are shown in Figure 4. The strain data derived from displacement measurements were used to plot the variation in strain over time for each specimen and their respective times to rupture, as depicted in Figure 5. As illustrated in Figure 5, all test results clearly showed the phases of primary creep, secondary creep, and tertiary creep, leading up to the final rupture of the specimens.

Figure 4. Specimens after the creep tests

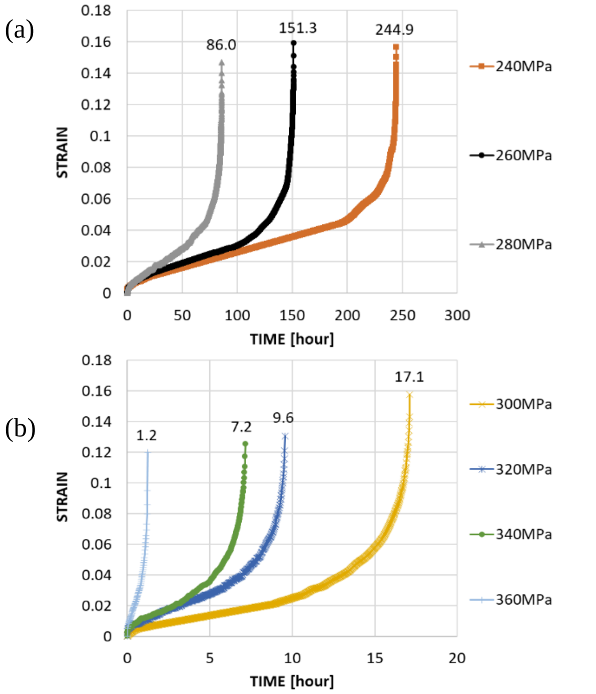

Figure 5. Test results of creep strain curves and rupture times

4. Analysis of the Creep Test Results

4.1 Comparative Analysis of the Creep Test Results with the ASME Code

The HBB-T-1400 (creep-fatigue assessment) procedure in the ASME B&PV Code, Sec. III, Div. 5, specifies the expected minimum stress to rupture as applied during the creep damage assessment of P91. The relationship between rupture life and stress follows a logarithmic decay; therefore, lifetimes were calculated using regression analysis, rather than simple linear interpolation, as shown in Figure 6. The rupture times calculated by applying the regression formula shown in Figure 6 to the stress values from our tests were compared with the experimental results and summarized in Table 1. For tensile stresses above 280 MPa listed in Table 1, the corresponding rupture times were extrapolated by the regression formula presented in Figure 6. The findings indicated that the creep rupture times were between 3.8 and 92.3 times longer than the requirements specified by the ASME Code, thereby demonstrating substantial safety margins and compliance with the code.

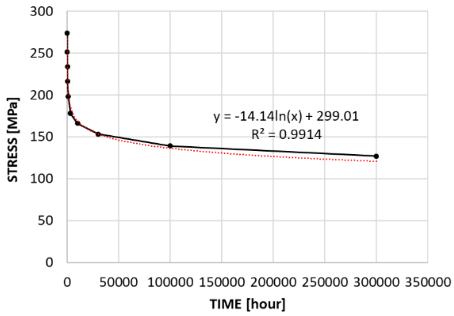

Figure 6. Creep rupture stress of P91 at 550˚C

Table 1. Creep test results compared with minimum creep rupture life of P91 at 550°C in ASME Code.

Specimen	Tensile stress [MPa]	ASME Code rupture time[hr]	Creep test rupture time[hr]
#1	240	65	244.9
#2	260	16	151.3
#3	280	3.9	86
#4	300	0.9	17.1
#5	320	0.22	9.6
#6	340	0.055	7.15
#7	360	0.013	1.2

4.2 Larson-Miller Parameter for P91

Using the results from various creep test loads and rupture times, the Larson-Miller Parameter (LMP) values were calculated, assuming a Larson-Miller Constant of 30[5]. These LMP values are tabulated in Table 2 and presented in Figure 7. This approach will be useful for predicting the creep rupture lifetimes under a range of untested load conditions in the future, enhancing the understanding of P91 steel's behavior under different stress levels.

Table 2. Larsen-Miller Parameters of creep test results

Specimen	Tensile stress [MPa]	Creep test rupture time[hr]	LMP P=823(logt+30)/1000
#1	240	244.9	26.656
#2	260	151.3	26.484
#3	280	86	26.282
#4	300	17.1	25.705
#5	320	9.6	25.498
#6	340	7.15	25.393
#7	360	1.2	24.755

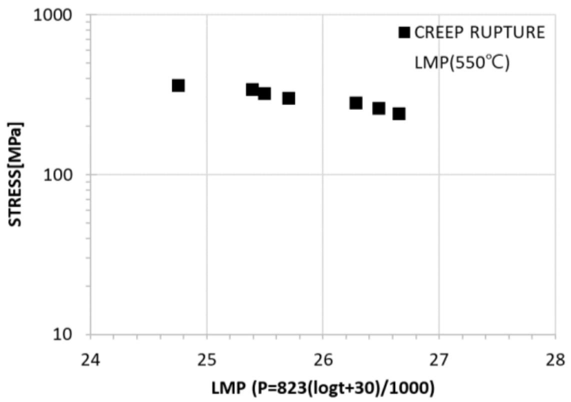

Figure 7. Lasen-Miller Parameter plot of creep test results

5. Conclusion

Creep tests on specimens of induction bent P91 pipes confirmed that their creep properties satisfy the stringent requirements of the ASME Code. Tests conducted under various tensile stresses from 220 MPa to 360 MPa at 550°C all met the ASME Code's creep rupture lifetime criteria. Based on these results, the Larson-Miller Parameter (LMP) for P91 at 550°C was calculated, enabling the prediction of creep rupture lifetimes under different load values. Thus, the study demonstrates that the effects of heating and bending by the induction process on the material's creep properties are minimal, affirming that induction bending is a viable process for the piping systems of the PGSFR.

Acknowledgement

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