Review of High Temperature Tensile Properties of P91 Steel for Induction Bent Pipe in Prototype Gen-IV Sodium-cooled Fast Reactor

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

1. Introduction

The Mod.9Cr-1Mo (P91) steel is an advanced material to be applied for the structures such as heat exchangers and pipes at high temperature condition in Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) developed in Korea. Also, it is a registered material in ASME Section III, Division 5 [1]. And efforts to enhance safety in the PGSFR by reducing sodium leaks, are being made to apply induction bending method to the piping systems [2,3], as an alternative to traditional welding methods.

The high-temperature tensile properties and other material property data of P91 induction bent pipe material are crucial for structural integrity assessments. Therefore, this study conducted tensile tests on material specimens, taken from the P91 induction bent pipe, at room and various high temperatures, and analyzed the results.

2. Tensile Tests and Reviews

50 mm long plate tension test specimens, which were made by collecting samples from induction bending pipe, were used for tensile tests as shown in Fig. 1. ASTM standards and ISO standard [4~6] were applied in this test. Table 1 shows the chemical composition of P91 steel. Tensile tests were performed at room temperature and several high temperatures from 200℃ to 550℃. High-strength steels like P91 are influenced by the strain rate at high temperatures, allowing for varying strain rates during tensile testing to accurately determine yield stress and tensile strength. In this study, tensile tests were initially conducted at a strain rate of 0.0002/sec, which was then increased tenfold to 0.002/sec. Test were also performed at a uniform strain rate of 0.001/sec. The results of these tests were compared and analyzed to understand the influence of strain rate variations on the material's tensile properties.

A high-temperature extensometer from MTS with a gage length of 12mm was used to measure strains. Fig. 2 shows the high temperature tensile test rig (MTS 370.10; capacity of 10 tons) which is located at the Center for Research Facility of Hanbat National University.

Table 1. Chemical compositions of the P91 steel (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

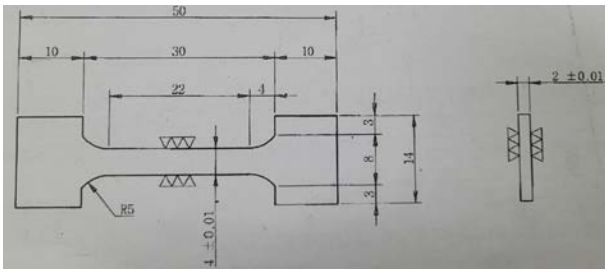

Fig. 1 Drawing of tensile test specimen (mm)

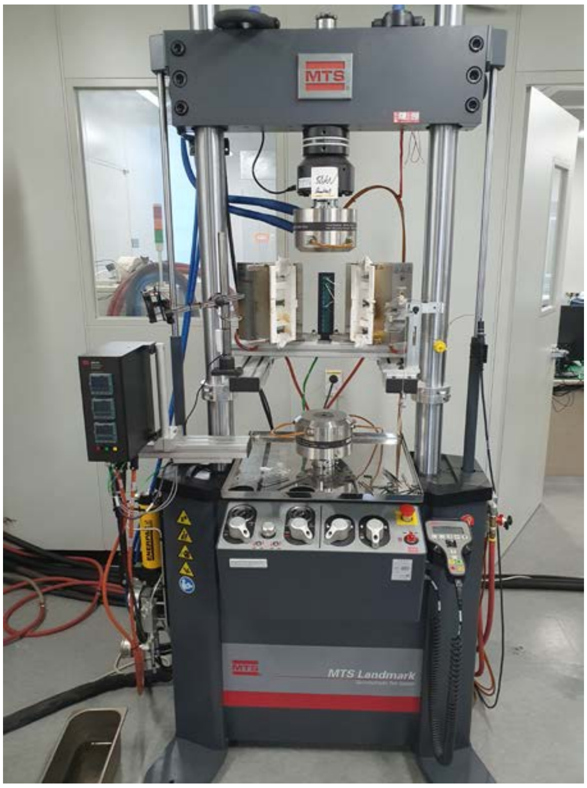

Fig. 2 Tensile test facility

Table 2. Tensile properties of the P91 steel (average)

Temperature (℃)	Young's modulus (MPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%, UTE)
20	222	642	770	27
200	217	589	693	19
300	201	559	650	14
400	192	531	617	16
500	165	477	533	26
550	162	415	471	35

Table 2 shows the resultant tensile properties of P91 at various temperatures, respectively. Young's modulus, yield strength (YS), tensile strength (UTS), and elongation are compared. At 550°C, the yield stress of P91 steel was observed to be 415MPa, exceeding the values of 269MPa and 254MPa in ASME Div5 and RCC-MRx [1, 7] Codes, respectively. Considering the scattering of the test data, the yield stress of the test can be inferred to be close to the upper limit values, given the Code's average property values. Fig.3 presents the tensile curves obtained from the tests at both room and high temperatures compared to the tensile curves provided in the RCC-MRx [7], illustrated up to a 1% strain range. Comparing these curves, it can be observed that the test values are generally higher than those specified by the Code. In the ASME Code [1], tensile curves at our test temperature conditions are not provided, so a direct comparison with the tensile test results is not available. However, the S_m(Design stress intensity) value of 550°C from the Code is 125MPa, and the value determined from the test results is 157MPa. This also indicate that the test value is higher than the Code's value. Therefore, since the tensile properties according to both Codes are higher than the test values, it has been confirmed that the tensile properties in the codes are conservative.

Fig. 4 shows the tensile curves of P91 steel at room and various elevated temperatures for a constant strain rate of 0.001/sec. As temperature increase, the tensile curves show both the yield strength and tensile strength decrease, whereas elongation exhibits a decrease followed by a increase with rising temperature, as shown in Table 2.

Fig. 5 illustrates the effect of increasing the strain rate from 0.0002/sec to 0.002/sec after determining the yield stress. At temperatures above 500°C, a notable "jump" in the tensile curve is observed due to the change in strain rate. This indicates that the tensile properties of P91 steel are influenced by the strain rate at high temperature, as detailed up to 2% strain in Fig. 6. In the figure, "S1" represents a constant strain rate of 0.001/sec, while "S2" shows the effect when the strain rate increases from 0.0002/sec to 0.002/sec. Under the "S2" condition at 500°C and 550°C, the tensile curve exhibits a stepwise increase by approximately 5.5% and 9.6% respectively, due to the influence of viscous stress from the tenfold increase in strain rate.

Comparing the effects of strain rates of 0.001/sec (S1) and 0.0002/sec (S2) on the initial parts of tensile curves, the curves show a increase of 2.2% and 7% for temperature of 500°C and 550°C respectively, at a higher strain rate. Furthermore, comparing strain rate of 0.001/sec (S1) and 0.002/sec (S2) in the latter part of the tensile curve, the curves show a increase of 1.7% and 1.9% for temperature of 500°C and 550°C, respectively, at a higher strain rate. This highlights the significant impact of strain rate, especially at higher temperatures, demonstrating a clearer effect as the temperature increases.

For high-temperature structural integrity evaluations of P91 material, it's crucial to apply viscoplastic constitutive equations. This necessitates the use of results from various tensile tests conducted at different strain rates to accurately determine the material constants for these equations, ensuring reliable and precise evaluations of P91 material's behavior under high-temperature conditions.

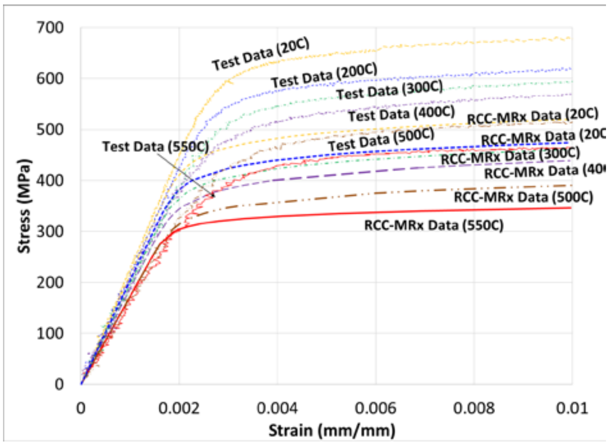

Fig. 3 Comparison of tensile curves of P91 between test data and RCC-MRx data

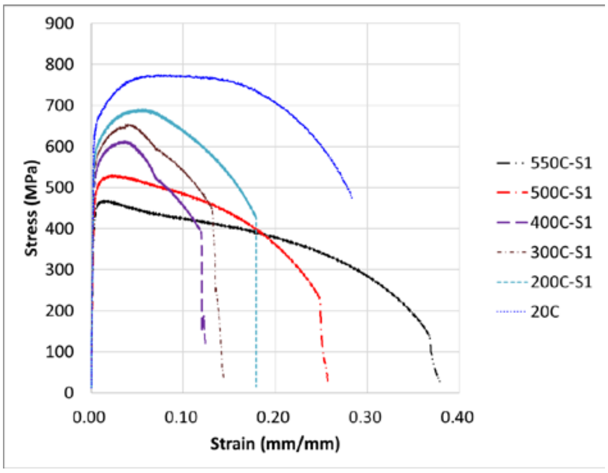

Fig. 4 Stress-strain curves of P91 steel (0.001/sec)

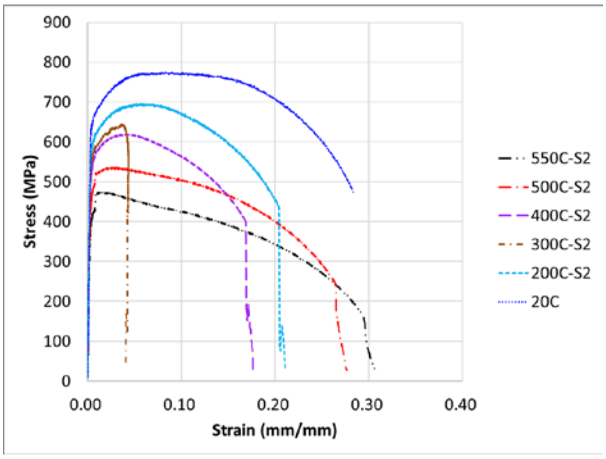

Fig. 5 Stress-strain curves of P91 steel (0.0002/s→0.002/s)

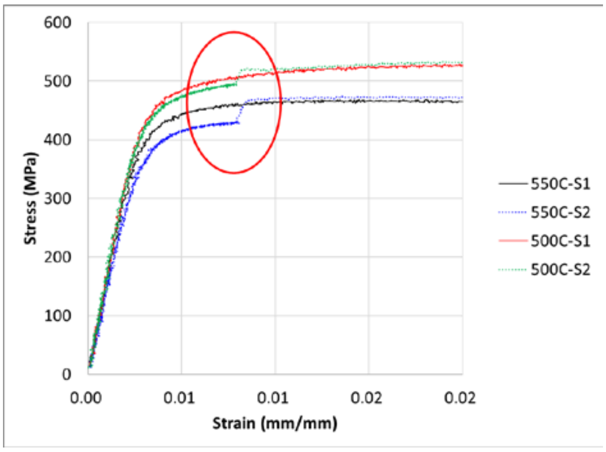

Fig. 6 Effect of strain rate on the tensile behavior of P91steel

3. Results and Discussion

In this study, tensile tests were conducted on specimens taken from P91 induction bent pipe under various temperature conditions and strain rates, and the resulting tensile curves were reviewed. These curves were compared with values provided by the RCC-MRx Code. It was observed that as the temperature increases from ambient 20°C to 550°C, the tensile curve lowers, indicating a reduction in yield stress and tensile strength, while elongation first decreases then increases. This study focused on analyzing tensile behavior at three different strain rates: 0.0002/sec, 0.001/sec, and 0.002/sec. The findings showed that below 500°C, changing strain rates had no impact on the tensile properties, but above 500°C, an increase in strain rate resulted in lowering tensile curves, highlighting the viscoplastic characteristics of P91 material. This temperature-dependent behavior underscores the need for applying accurate viscoplastic constitutive equations in high-temperature structural integrity evaluations of P91 material. Additionally, since the tests performed in this study was conducted on samples for one heat and applied the limited strain rates, it is hoped the results of the tests can be enriched by performing tests applied with more samples from more heats and various strain rates in the future.

Acknowledgement

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 tothe 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] ASTM E8-04, Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, 2004.

[5] ASTM E21-03a, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials, ASTM International, 2004.

[6] ISO 6892-2, Tensile Tests on Metals – Test Method at Elevated Temperature, 2018.

[7] RCC-MRx, Section III – Tome 1 – Subsection Z – Appendix A3.18AS : Properties Groups for products and parts in alloy steel grade X19CrMoVNb9-1 normalized-tempered or quenched-tempered (P91 family), AFCEN, 2022.