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HIGH TEMPERATURE FATIGUE TESTS AND CREEP TESTS OF P91 MATERIAL SUBJECTED TO INDUCTION PIPE BENDING PROCESS

Jong-Bum Kim[a*], N.H. Kim[a], S.K. Kim[a], C.G. Park[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 which was developed by ORNL is an advanced material to be applied for the structures such as heat exchangers and pipes at high temperature condition in sodium-cooled fast reactor(SFR). It is a registered material in ASME Section III, Subsection NH or Division 5 [1].

In order to reduce the potential leakage in P91 piping of a SFR, induction bending technology was applied instead of the existing welding manufacturing method to reduce the number of welds in piping layout including elbow. Since induction bending is carried out by heating at very high temperatures above 900℃, it is necessary to examine how the properties of the P91 piping material change relative to the parent material and also to assess the satisfaction of the requirements in ASME B&PV Code, Section III, Division 5. To this end, the applicability of induction bending technology of P91 piping was investigated with tensile tests, impact tests, and hardness tests, before and after induction bending process [2]. Also the corresponding material properties were checked to judge the satisfaction of the requirements of ASME Division 5 although further tests are necessary to check the high temperature fatigue properties and creep properties.

In this study, the applicability of induction bending process is assessed by conducting the high temperature low cycle fatigue tests and creep tests to collect the test database and by the confirmation of the satisfaction of Code requirements for high temperature material properties.

2. Low Cycle Fatigue Tests

Fig. 1 shows the pipe made of induction bending process and outer diameter and thickness of the pipe are 559 mm and 12.7 mm, respectively. Chemical composition of the P91 pipe is shown in Table 1. Two specimens were prepared for fatigue test, respectively, at the five locations such as tangent(F1), extrados(F2), intrados(F3), transition(F4), and neutral(F5) as shown in Fig. 1. The high temperature low cycle fatigue test was conducted per test procedure [3] for 10 specimens. The dimension of the low cycle fatigue test specimen is shown is Fig. 2. Tests were performed by using MTS electro-hydraulic servo fatigue test machine of which capacity is 100kN at 550℃. Strain control loading was applied sinusoidally at 0.004/sec speed with 1% strain range and load ratio of -1.

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

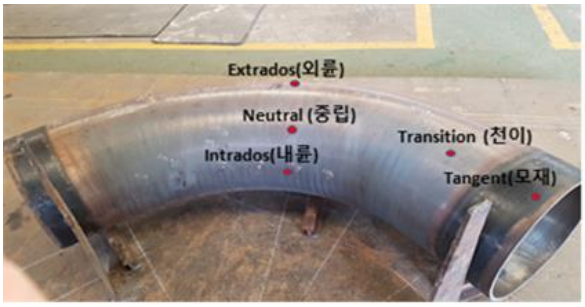

Fig. 1 Induction Bended Pipe and Specimen Locations

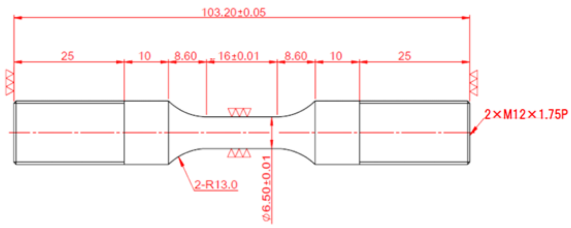

Fig. 2 Low Cycle Fatigue Test Specimen (mm)

The results of the high temperature low cycle fatigue test are summarized in Table 2. The first column represents the ID of the specimen, followed specimen locations (F1 through F5). The last column represents the cycles to failure, which is the fatigue life time, when the maximum tensile load is reduced by 50% or when the specimen is separated into two pieces. The low cycle fatigue lives for 10 specimens were compared in Fig. 3, with the average value of each location being 1945 (F1), 1566 (F2), 1658 (F3), 1696 (F4), and 1418 (F5) cycles, respectively. The fatigue life of extrados, intrados, transition, and neutral parts decreases by 14.8%, 27.1%, 19.5%, and 12.8% respectively compared to that of parent material (F1). Although fatigue life in neutral location turned out to be smaller than those of the thinner extrados and the thickened intrados due to induction bending, it is difficult to give much meaning by considering the scattering range of fatigue test results in general. The design fatigue life at 550˚C required for P91 steel in ASME code [2] is 93 cycles, and the results of this experiment show that fatigue lives at all locations satisfy the design requirements with sufficient margin.

Table 2. High Temperature Low Cycle Fatigue Tests Results

Specimen ID	Specimen Location	Test Temp. (℃)	Gage length (mm)	※1 $N_f/2$(hysteresis loop obtained closest to $N_f/2$) or N_{stop} Number of cycle N (cyc.)	Maximum Stress (MPa)	Minimum Stress (MPa)	Total Strain $\Delta\varepsilon_t$ (%)	Elastic Strain $\Delta\varepsilon_e$ (%)	Plastic Strain $\Delta\varepsilon_p$ (%)	Total Stress (MPa)	Cycles to failure N_f (cyc.)
F1-1	Tangent - Longitudinal	550	12	1,000	383	-396	0.99	0.51	0.48	779	2,079
F1-2	Tangent - Longitudinal	550	12	900	380	-391	1.00	0.49	0.51	771	1,812
F2-1	Extrados - Longitudinal	550	12	800	297	-303	1.00	0.36	0.64	600	1,523
F2-2	Extrados - Longitudinal	550	12	800	292	-304	1.01	0.35	0.66	596	1,609
F3-1	Intrados - Longitudinal	550	12	900	339	-352	1.00	0.42	0.58	691	1,803
F3-2	Intrados - Longitudinal	550	12	800	346	-357	1.00	0.44	0.56	703	1,513
F4-1	Transition (start) - Transverse	550	12	800	381	-394	1.00	0.47	0.53	775	1,642
F4-2	Transition (start) - Transverse	550	12	900	356	-372	1.00	0.45	0.55	728	1,750
F5-1	Neutral - Longitudinal	550	12	700	310	-324	0.99	0.39	0.60	634	1,358
F5-2	Neutral - Longitudinal	550	12	700	309	-317	1.00	0.38	0.62	626	1,478

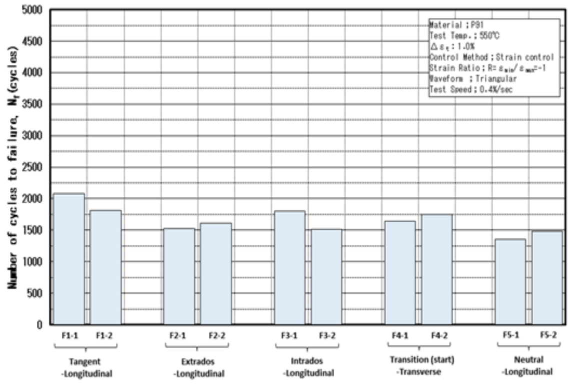

Fig. 3 Comparison of Fatigue Lives

3. Creep Tests

The creep tests were conducted by collecting two specimens from each of three locations; that is, tangent, extrados, and neutral locations. The dimension of a creep test specimen is shown in Fig. 4. The tests were performed per creep test procedure [4] by establishing test conditions under which creep rupture could occur within 4,190 hours considering limited time and resources of this study.

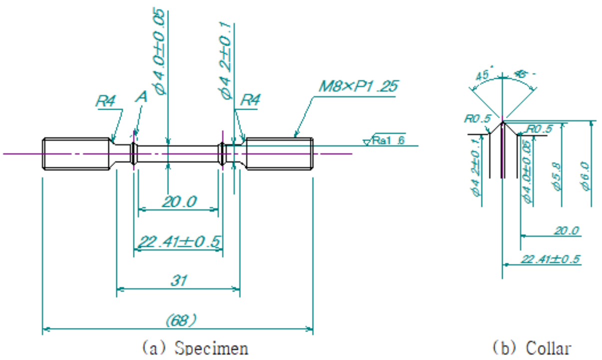

Fig. 4 Creep Test Specimen (mm)

Fig. 5 shows the creep strains and creep strain rates measured in the creep test conducted over 4,190 hours. The 6 specimens all show the primary creep behavior of decreasing creep strain rate for the first 500 hours and then secondary creep behavior with constant creep strain rate. However, all tests did not reach the tertiary creep as predicted at the beginning.

After 4,190 hours, the tangent location (C1) showed 0.32% to 0.47%, the extrados location (C2) showed 2.04% to 2.08%, and the neutral location (C3) showed 1.84% to 2.04% of total creep strains. The minimum creep strain rate (that is gradient of secondary creep strain) of tangent location was 0.000032 to 0.000038%/hr, and those of the extrados and neutral locations were 0.0003 to 0.00034%/hr. The two specimens collected from three locations showed consistent results. The creep strain rate of parent material (tangent location) was significantly lower than those of the extrados and the neutral locations. Even though extrados and neutral locations affected by induction bending process may be judged to have weaker creep properties than the parent material, it is not yet appropriate to reach a conclusion due to the scattering nature of the creep test and small amount of test data.

In this study, it is noted that the creep strain on extrados and neutral parts, which are affected by induction heat, differed significantly from the creep strain on tangent part (parent material). The calibration of the instruments and sensors and the dimensional examination of the specimen were checked again to investigate the potential errors during test. There were no errors found in the test procedure and it is judged that the difference in test results was due to scattering nature of data that could actually occur.

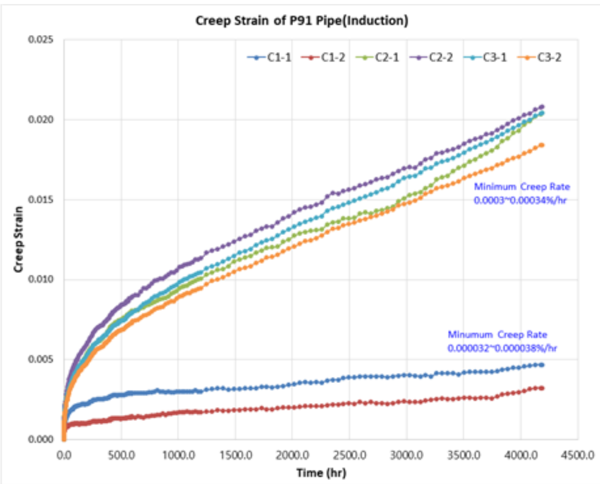

Fig. 5 Creep Test Results

The design creep rupture time required for P91 steel in ASME code [2] is 267 hours. The results of this experiment show that the ASME design requirements are satisfied with sufficient margin because no creep rupture occurred over 4,190 hours, which are much longer than the design creep rupture time, at all locations.

3. Results and Discussion

High temperature low cycle fatigue tests and creep tests were conducted on the specimens collected from various locations of the P91 pipe made of induction bending process to investigate whether the ASME Code requirements are met. From the results of low cycle fatigue tests and creep tests, it was confirmed that design fatigue life and design creep rupture time were satisfied with a sufficient margin.

As a result of the current study, the applicability of the P91 pipe by the induction bending process to reduce the number of welds to increase the structural integrity was confirmed and it is needed to carry out actual plant application test to confirm the satisfaction of other interface requirements in future.

Acknowledgement

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REFERENCES

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[4] Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials, ASTM E 139-11, ASTM, 2018.