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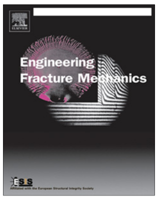

Effects of long-time service at high temperature on the material strength and J-R curve of Grade 91 steel

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ABSTRACT

The effects of long-time service at high temperature on the material strength, ductility, and J-Resistance behavior of Mod.9Cr-1Mo (ASME Grade 91) steel were investigated based on tensile and J-R tests with virgin and service-exposed Gr.91 steel specimens. The service-exposed Gr.91 steel specimens were sampled from a tee junction in a reheat steam piping system of an ultra-supercritical (USC) plant in Korea with an accumulated operation time of 73,716 h. Comparisons of the test data were made not only between the test results of the virgin materials and service-exposed materials but also between the test results and the material properties in the elevated temperature design (ETD) codes. These test data of yield strength (YS) and tensile strength (TS) for the virgin and service-exposed Gr.91 steel were compared with those of the ETD code, which showed that the current ETD code overestimates the YS and TS properties for long-time service in a non-conservative manner for Gr.91 steel. J-R test data currently not available in ETD codes were produced over a range of temperatures for virgin and service-exposed Gr.91 steel. The effects of long-time service in J-R curve were investigated.

1. Introduction

The influence of long-time service at high temperature has recently been an important issue in high-temperature components of Generation IV (hereafter Gen IV) nuclear reactor systems [1,2] and ultra-supercritical (USC) plants operating under a creep regime because the degree of actual degradation in service-exposed materials has been found to be more severe than generally anticipated, especially for Grade 91 steel [2–4].

The target design lifetime of a Gen IV reactor system is 60 years or more. It is generally known that the material strength and fracture toughness in such systems tend to degrade as the operation time accumulates. However, the elevated temperature design (ETD) codes [5–8] do not fully address the material degradation issues. Currently, ASME Section III Subsection NH [5] (ASME-NH) takes long-time service effects into account only regarding yield strength and tensile strength, while RCC-MRx considers thermal aging with thermal aging coefficients but most of the coefficients are left blank.

Abbreviations: ASME-NH, ASME Section III Division 1 Subsection NH; CCG, creep crack growth; DHX, decay heat exchanger; ETD, elevated temperature design; FHX, forced-draft sodium-to-air heat exchanger; Gen IV, generation IV; Gr.91, Grade 91; J-R, J-integral Resistance; LBB, Leak Before Break; SFR, Sodium-cooled Fast Reactor; SG, Steam Generator; TS, Tensile Strength; USC, Ultra Super Critical; YS, Yield Strength.

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The effects of long-time service on the yield strength (YS), tensile strength (TS), ductility, and fracture behavior of Gr. 91 steel were investigated in this study to quantify the degradation of the material in terms of material strength and J-R properties based on a series of material test results from virgin and service-exposed Gr.91 steel. Service-exposed Gr.91 steel materials sampled from a reheat steam piping system of an ultra-supercritical plant with an accumulated operation of 73,716 h were used for the material testing. The test results of the service-exposed Gr.91 steel were compared with those of virgin Gr.91 steel, and the test data were compared with those of the ETD codes [5,7–9].

2. Grade 91 steel before and after long-time service

2.1. Virgin Gr. 91 steel

Mod.9Cr-1Mo (ASME Grade 91) steel is a promising material candidate for the main components in sodium-cooled fast reactors [1]. Gr.91 steel is a ferritic-martensitic heat resistant steel and one of the two main materials with austenitic stainless steel 316 to be used in Korean Gen IV SFRs [1].

Gr.91 steel has a lower thermal expansion coefficient and higher thermal conductivity than austenitic stainless steel 316. The thermal conductivity of Gr.91 steel is higher by a maximum of 36.9% at 100 °C and 21.2% at 550 °C, while the thermal expansion coefficient of Gr.91 steel is lower by a maximum of 51.3% at 250 °C and 48.8% at 550 °C in comparison with those of austenitic 316 stainless steel [4] so that less thermal stress and more efficient heat transfer can be expected when Gr.91 steel is used in heat exchangers. However, there is a concern about the so-called Type IV cracking at welded joints in Gr.91 steel and careful post weld heat treatment at the welded joint is required [10–14]. The microstructures of Gr.91 steel are relatively unstable.

The chemical compositions of Gr.91 steels in the ETD codes [15,16] for Gr.91 steel plate, forged Gr.91(F91) steel in the ASME code, unexposed original Gr.91 steel, and the KAERI virgin plate used for fabrication of the material specimens in the present study are given in Table 1. As shown in Table 1, the RCC-MRx code restricts the carbon range more strictly, and a higher carbon from 0.06 to 0.08 would improve the creep strength, and decreasing the upper limit from 0.15 to 0.12 would increase the microstructure stability by the suppression of carbide coarsening and undesirable phase formation [17]. The service-exposed Gr.91 steel was sampled from a tee fitting of forged Gr.91 (F91) steel in a USC plant. The chemical compositions were within the range of ASME F91 as shown in Table 1.

In the present study, virgin Gr.91 steel material specimens were made with the ‘KAERI virgin plate’ rather than the ‘unexposed original’ Gr.91 steel in Table 1, which is not from the same heat of the service-exposed Gr.91 steel. It should be ideal to use the same heat material with the unexposed original Gr.91 steel in material testing. In reality, however, it is hard to secure the original material and even the mill sheet because it is either confidential or impossible to obtain. It is expected that the differences in the chemical compositions of the original batch and KAERI’s batch might not result in big differences in the tensile strengths and J-R curves.

In previous study [18], ductility of Gr.91 steel has been reported minimum at 400 °C in a range of temperatures from room temperature to 700 °C. Since ductility minimum at a certain temperature may result in weak fracture toughness, J-R tests over a range of temperatures from room temperature to 600 °C were carried out to investigate the J-R behavior around 400 °C in this study.

2.2. Long-time service-exposed Gr.91 steel

It is known that Gr.91 steel degrades more severely under long-time service at high temperature compared with austenitic stainless steel 316 [2]. Thus, the effects of thermal aging were investigated, and a comparison was made regarding the strength reduction factors from long-time service in the ASME-NH [5].

Table 1
Chemical compositions of Grade 91 steel (wt.%).

Code/test	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Others
ASME (Gr.91 plate)	0.06–0.15	0.25–0.66	0.025	0.012	0.18–0.56	0.43	7.90–9.60	0.80–1.10	0.025–0.08	0.02	
RCC-MRx (Gr.91 plate)	0.08–0.120	0.30–0.60	≤0.02	≤0.005	0.20–0.50	≤0.20	8.00–9.50	0.85–1.05	0.03–0.07	≤0.04	Nb 0.06–0.10
ASME (F91)	0.08–0.12	0.3–0.6	0.025 max	0.025 max	0.2–0.5	0.4 max	8.0–9.5	0.85–1.05	0.18–0.25	Al 0.02	Nb 0.03–0.07 Ti 0.01 Zr 0.01
Unexposed, original (Gr.91)	0.08	0.38	0.018	0.003	0.34	0.29	8.75	0.875	0.242	0.014	Nb 0.079
KAERI Virgin plate (Gr.91)	0.115	0.415	0.012	0.0014	0.23	0.22	8.9	0.869	0.0513	0.014	Nb 0.079 N 0.038

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