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Influence of Thermal Aging on Material Strength Behavior in Grade 91 Steel

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1. Introduction

Recently thermal aging has become one of the important issues in heat resistant materials targeted for power plant components operating at elevated temperature. Mod.9Cr-1Mo (ASME Grade 91, hereafter 'Gr.91') is known to be affected in material strength, ductility and fracture toughness as the components made of Gr.91 is aged in the power plants including Generation IV nuclear systems. In this study, the influence of thermal aging on yield strength and ductility for Grade 91 steel has been investigated.

Service exposed Gr.91 steel materials sampled from a piping system of an ultra-supercritical plant over 73,716 hours were used for material testing. The test results were compared with those of the virgin Gr.91 steel and those data were compared with RCC-MRx data [1,2].

It should be noted that ASME Section III Subsection NH[3] has commenced from 2013 edition to treat thermal aging effect and the effect of strength reduction have been taken into account in yield strength(YS) and ultimate tensile strength(UTS). However, the influence of thermal aging for Gr.91 has not been fully covered because it provides the reduction factors only for UTS.

In case of RCC-MRx[2] thermal aging influence is taken into account only for case of austenitic stainless steel and J-resistance properties.

Present study shows the effect of thermal aging for Gr.91 in case it has been subjected to 73,716 hours.

Gr.91 steel has low thermal expansion, high thermal conductivity and high strength. Gr.91 steel is a promising candidate material for secondary piping, heat exchangers, and steam generator in a Generation IV sodium-cooled fast reactor (SFR)[3]. Gr.91 steel has been adopted as one of the two main materials along with austenitic stainless steel 316 for Korean Gen IV SFR components as shown in Fig. 1 and is being widely adopted in Gen IV nuclear reactor systems.

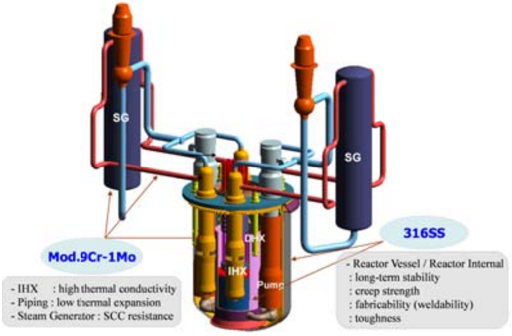


Fig. 1 Two main materials in Generation IV Sodium-cooled Fast Reactor

2. Comparison on material behaviors with and without thermal aging

Fig. 2 shows comparison of the Gr.91 steel yield strength(YS) among the KAERI's test results of virgin material and service exposed (73,716 hrs, 8.4 years) material, and three other design code properties.

The important point in Fig. 2 is the YS has dropped as much as maximum 35.8% under approximately 8.4 years exposure at temperature of 596°C and 40kg/cm^2 (steady state), which means that some yield strengths dropped below the code material properties. It is to be noted that serration flow was observed at the temperature range of 350°C to 450°C in the test data which is apparently linked to dynamic strain aging.

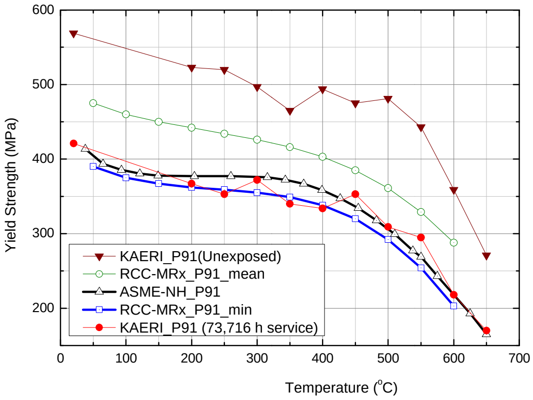


Fig. 2 Comparison of yield strength in design codes and test results with virgin and service exposed material

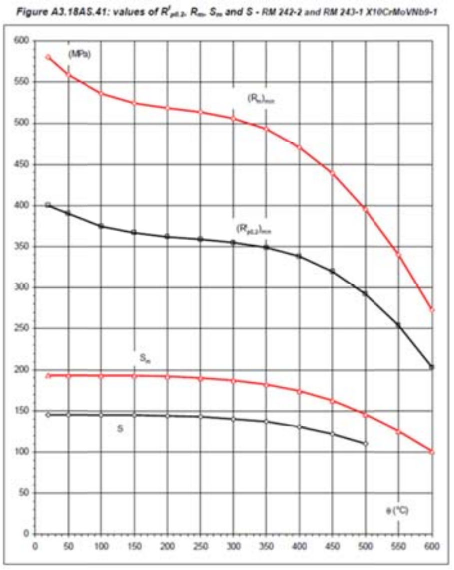
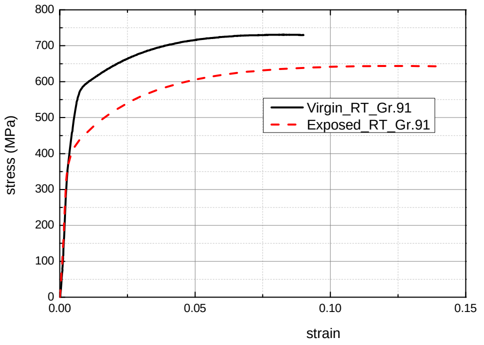


Fig. 3 Ultimate strength, yield strength and maximum allowable stresses of Gr.91 steel in RCC-MRx

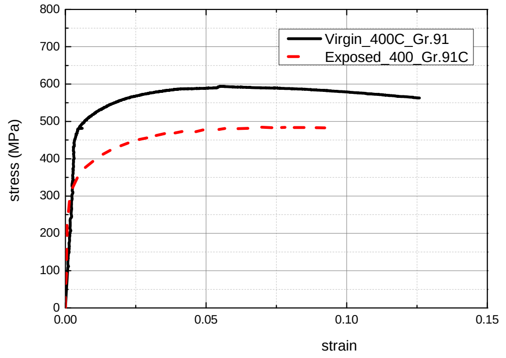
Fig. 3 shows UTS, YS, design stress intensity and maximum allowable stresses for Gr.91 steel as a function of temperature.

The design life of the Gen IV SFR is targeted as 60 years although currently the creep rupture strength data [1,4] are available up to 300,000 hours (~40 years considering availability factor). Fig. 2 shows that YS of thermally aged material should drop far below the code material properties as the plant operation time is accumulated more, say 20, 30 and 40 years. The material strength data in RCC-MRx shows that there is no data or guide for thermally aged materials as shown in Fig. 3.

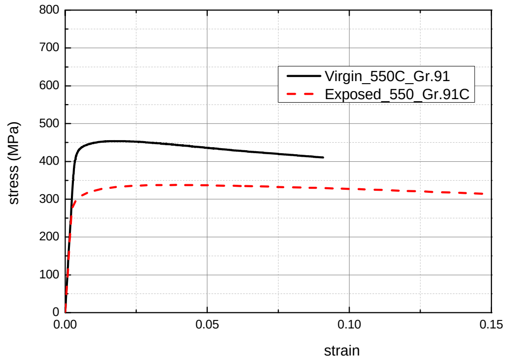
When comparing the stress–strain behavior between virgin material and service exposed material, it was shown that the stress has been dropped maximum 31.1% at room temperature, 22.7% at 400°C and 30.4% at 550°C as shown in Fig. 4.



(a) room temperature



(b) 400°C



(c) 550°C

Fig. 4 Stress-strain relationship for virgin Gr.91 steel and service exposed (73,716 hours) Gr.91 steel

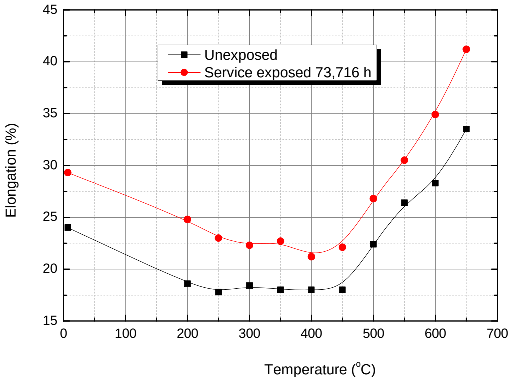


Fig. 5 Comparison of elongation for virgin material and service exposed material

3. Ductility behavior

The elongation behavior of the Gr.91 steel before and after thermal aging is shown in Fig. 5 as function of temperature. It is shown that the elongation is improved as much as maximum 23% as the aging is going on as shown in Fig. 5 while material strength becomes degraded as shown in Fig. 2. The other thing of importance is that ductility becomes minimum over the temperature range of 300°C to 450°C which is exactly the range of serration flow in Fig. 2, which means that ductility minimum at the temperature range of serrate flow is one of the typical phenomena of dynamic strain aging. It is out of the scope of this paper and study on the DSA as a function of temperature and strain rate is now separately being conducted.

Elongation properties are provided in RCC-MRx[2] only for austenitic stainless steel of 316L(N) and 316L but the properties are not provided for Gr.91 steel. Similarly, fracture properties for austenitic stainless steel are relatively well provided compared to Gr.91 steel in RCC-MRx [1,2] and some modifications in the material properties were shown to be necessary in RCC-MRx [5].

4. Conclusions

In this study, thermal aging effect of Gr.91 steel on the strength and ductility has been investigated. It was shown that yield strength has dropped as much as 35.8% over the service exposed duration of 8.4 years while ductility has been improved up to 23%. Since the present design rules of ASME Code [4] and RCC-MRx do not provide concrete strength reduction factors for the thermal aging, it was shown to be necessary based on the findings of the present study to take this thermal aging influence into account in those design codes so that the design outcomes are to be more reliable.

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