Transactions of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 29-30, 2008

The Effect of Material Variability on Fatigue Behaviors of Low Alloy Steels in 310°C Deoxygenated Water

Hun Jang [a], Hyunchul Cho [b], Changheui Jang [a*], In Sup Kim [a]
[a] *Department of Nuclear and Quantum Engineering., Korea advanced institute of science and technology.*
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] *Doosan Heavy Industries & Construction Co., Ltd.*
555 Gwigok-Dong, Changwon, Gyeongnam 641-792, Republic of Korea
[*] *Corresponding author: chjang@kaist.ac.kr*

1. Introduction

As environmental fatigue damage is one of the main crack initiation mechanisms in nuclear power plants (NPPs), it is most important factor to assess the integrity and safety of NPPs. So, based on extensive researches, argon nation laboratory (ANL) suggested the statistical model to predict fatigue life of low alloy steels (LASs) which are widely used as structural material in NPPs [1]. Also, we reported the environmental fatigue behaviors of SA508 Gr.1a LAS [2]. However, from comparison between our experimental fatigue data and ANL's statistical model, our fatigue life data showed poor agreement with the ANL's statistical model.

In this regard, the additional low cycle fatigue (LCF) tests were performed in 310°C deoxygenated water, and compared with ANL's statistical model to evaluate reliability of the data. And then, the effect of material variability on the fatigue life of LASs was investigated through microstructure analysis.

2. Experimental

2.1 Test Materials

The test materials were SA508 Gr.1a LAS – heat A, SA508 Gr.1a LAS – heat B which are used as piping material of the reactor coolant system, and SA508 Gr.3 LAS which is used as the reactor vessel material.

The tensile properties measured in RT and 310°C air are summarized in Table 1. The SA508 Gr.3 LAS showed the highest tensile property. And two heats of SA508 Gr.1a LAS showed very similar tensile properties.

Microstructures of SA508 Gr.1a LAS – heat A, SA508 Gr.1a LAS – heat B, and SA508 Gr.3 LAS are shown in Fig. 1. SA508 Gr.1a LAS – heat A consists of pearlite and ferrite. SA508 Gr.1a LAS – heat B and SA508 Gr.3 LAS contain tempered bainite.

Table 1: Tensile property of each LASs

Material	Y.S. (MPa)		U.T.S. (MPa)	
	RT	310°C	RT	310°C
SA508 Gr. 1a-heat A	350.8	243.3	521.2	521.9
SA508 Gr. 1a-heat B	345.3	258.6	522.1	542.5
SA508 Gr. 3	482.5	439.1	633.0	616.9

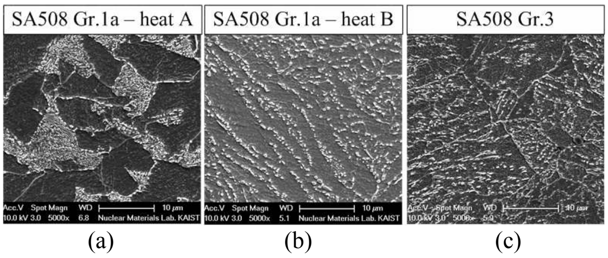


Fig. 1. Microstructure of each LASs: (a) SA508 Gr.1a - heat A, (b) SA508 Gr. 1a – heat B, (c) SA508 Gr.3.

2.2 Test Conditions

The LCF tests were conducted at a strain rate of 0.04 %/s and the strain amplitudes of 0.4 and 0.8 %. The DO level in water was maintained less than 1 ppb. Additionally, the conductivity was kept under 0.1 S/cm during the LCF tests.

3. Results and Discussion

3.1 Fatigue Life of each LASs

The fatigue life of SA508 Gr.1a LAS – heat A showed the shortest fatigue life among each LASs, and the fatigue life of SA508 Gr.1a LAS – heat B had the longest fatigue life as shown in Fig. 2. Although our test results are very limited, the difference of fatigue life of LASs showed consistently at the strain amplitudes of 0.4 and 0.8 %. The fatigue life data of SA508 Gr.1a LAS – heat B and SA508 Gr.3 LAS is more close to the ANL's model, relatively. Therefore, it is thought that our fatigue life data have enough reliability.

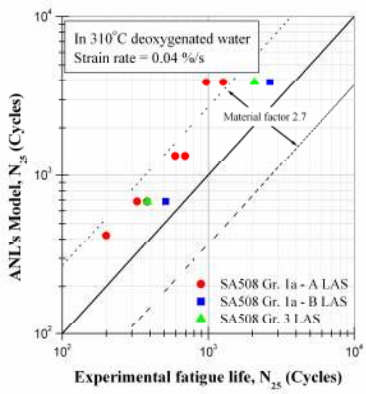
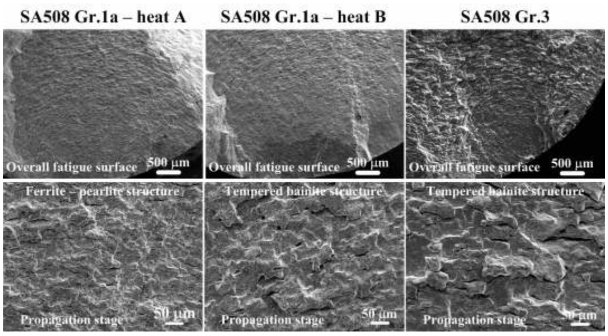


Fig. 2. Fatigue life of each LASs in 310°C deoxygenated water.

3.2 Fatigue Surface Observation

Figure 3 shows the overall fatigue surface and its propagation stage of each LASs tested at a strain rate of 0.04 %/s in 310^{o}C deoxygenated water. The overall fatigue surface of SA508 Gr.3 LAS shows more rugged fracture surface relatively as shown in Fig. 3 (c). As the low ductility and high yield strength of SA508 Gr.3 LAS could possess a limited capacity for deformation and crack tip blunting, the stress intensity at the crack tip may be increased, and resulted in rugged fatigue surface and increase of the fatigue crack growth rate.

The fatigue surface in propagation stage of SA508 Gr.1a LAS – heat A represented the striation-like features in ferrite phase, which are characterized by stage II cracking [3]. However, in case of SA508 Gr.1a LAS – heat B and SA508 Gr.3 LAS which have tempered bainite structure, the rugged and less striations were observed. Therefore, it is thought that the fracture mode of tempered bainite steels could not be fully followed by stage II cracking, and influenced by their microstructure.



(a) (b) (c)

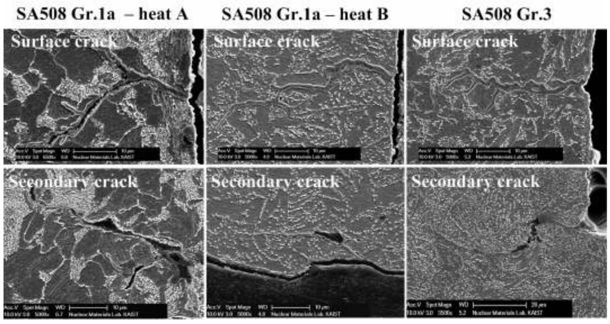
Fig. 3. Fatigue surfaces of each LASs: (a) SA508 Gr.1a – heat A, (b) SA508 Gr. 1a – heat B, (c) SA508 Gr.3.

3.3 Sectioned Area Observation

Figure 4 shows the surface and secondary cracks of each LASs. As shown in Fig. 4 (a), the surface and secondary cracks of SA508 Gr.1a LAS – heat A grew into ferrite phase and ferrite – pearlite phase boundary. The fatigue crack growth rate in pearlite phase could be decreased significantly because the pearlite phases act as strong barrier to crack propagation [3]. However, as the cyclic deformation of ferrite phase could be restricted by pearlite phase at the fatigue crack tip, the local strain and stress at the ferrite – pearlite phase boundary could be increased. It can accelerate the fatigue crack growth rate growing along ferrite – pearlite phase boundary.

On the other hand, in case of SA508 Gr.1a LAS – heat B and SA508 Gr.3 LAS, the surface and secondary cracks grew into ferrite phase between carbides in cementite lath as shown in Fig. 4 (b), (c). The carbides play as an obstacle decreasing the fatigue crack growth rate. As the fatigue crack growth could be more frequently confronted with homogeneous carbides, the fatigue crack growth could be retarded effectively due to homogeneous carbides. Consequently, the surface and secondary crack grow rate in ferrite – pearlite phase could be higher than that in tempered bainite phase.

The micro-voids induced by hydrogen induced cracking mechanism in secondary cracks were observed [2]. The secondary cracks might be generated by the linkage with main fatigue crack and micro-voids during the fatigue crack growth, thereby enhancing the main fatigue crack growth [2]. Therefore, higher crack growth rate of surface and secondary cracks of SA508 Gr.1a LAS – heat A could be the cause of difference of fatigue lives of each LASs.



(a) (b) (c)

Fig. 4. Sectioned areas of each LASs: (a) SA508 Gr.1a – heat A, (b) SA508 Gr. 1a – heat B, (c) SA508 Gr.3.

4. Conclusions

1. The fatigue lives of each LASs were increased following order; SA508 Gr.1a LAS – heat A, SA508 Gr.3 LAS, and SA508 Gr.1a LAS – heat B.

2. From microstructure observation, the fatigue surfaces on SA508 Gr.1a LAS – heat B and SA508 Gr.3 LAS show relatively less striations than that of SA508 Gr.1a LAS – heat A by their homogeneous carbides.

Surface and secondary cracks of each LASs grow into ferrite phase and phase boundaries. During fatigue crack growth process, the restricted strain at the pearlite crack tip could accelerate the crack growth rate along ferrite – pearlite phase boundaries. Also, homogeneous carbides could more effectively decrease the crack growth rate.

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