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Creep-Fatigue and Fatigue Crack Growth Properties of 316 LN Stainless Steel at High Temperature

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ABSTRACT

High temperature fatigue crack propagation and fatigue-creep tests were carried out to investigate high temperature fatigue-creep properties of 316LN and 316L stainless steel. Fatigue crack growth tests of 316LN stainless steels were conducted with CT type specimens at various load ratios(R=0.1, 0.2 and 0.5) at 25℃~600℃. Fatigue-creep tests were carried out for two stainless steels types(0.04% N, 0.1% N) with a strain rate of 2 x 10^{-3}, a strain range of 0.1% and a holding time of 10 minutes at 600℃. The effects of microstructure, such as grain size(80~130μm), martensitc transformation and the dislocation structure around crack tip on fatigue crack resistance, were investigated. It was shown that the high temperature fatigue and creep-fatigue resistance of 316LN stainless steel improved significantly with the addition of nitrogen in steel. The increase in the fatigue resistance of 316LN stainless steel is related to the dislocation structure.

1. INTRODUCTION

It is important to consider high temperature failure problems of structural materials during design stage of liquid metal reactor. 316LN stainless steel which has good high temperature creep and fatigue properties was developed for the candidate structural materials for liquid metal reactor. It was reported that nitrogen addition to austenitic stainless steel improves tensile and fatigue properties of the alloys by some researchers[1-5]. But the roles of nitrogen for the improvement of fatigue properties of the alloys during fatigue cycle are not clearly understood.

High temperature fatigue crack propagation and fatigue-creep tests were carried out to have material data for reactor design and to investigate the effect of N addition on the high temperature fatigue and fatigue-creep properties of 316L and 316LN stainless steel for liquid metal reactor. The fatigue properties of 316LN stainless steel is discussed in relation with strain induced martensite transformation and the dislocation structure in cyclic plastic stain zone at growing fatigue crack tip.

2. EXPERIMENT

2.1. Materials

316L(0.04% N) and 316LN(0.14% N) stainless steels were prepared to perform fatigue crack growth tests for investigating the effects of nitrogen addition on the materials. The chemical composition is showed in Table 1. Specimens were fabricated from plates of 316L and 316LN stainless steels which were annealed after hot working. 316LN stainless steel specimens with different grain sizes were prepared by solution treatments in different temperatures. Specimens with grain size of 86μm and 126μm were prepared by solution treatment at 1050℃ and 1350℃ respectively and following water quenching. The grain sizes of the specimens were measured according to ASTM E 112-85 by image analyzer of PGT Co. The 316LN stainless steels with two different nitrogen contents(0.04% N, 0.1% N) for fatigue creep test were prepared by vacuum melting and hot rolling.

2.2. Fatigue Tests

Fatigue crack growth tests were carried out for 316L(0.04% N) and 316LN(0.14% N) stainless steel at 25℃~ 600℃. Compact tension(CT) type specimens with width of 25 mm and thickness of 5 mm were used for fatigue crack growth test. Tests were carried out according to ASTM E647. Cyclic fatigue loads between 80Kg and 400Kg with frequency of 1Hz were applied with Instron tensile test machine. Direct current potential drop(DCPD) method was used to measure fatigue crack length. Fatigue-creep tests were carried out for two stainless steels types(0.04% N, 0.1% N) to investigate the effect of fatigue-creep interaction with a strain rate of 2×10^{-3}/sec, a strain range of 0.1% and a holding time of 10 minutes at 600℃.

2.3 Analysis

Strain induced martensites on the fracture surface of 316L and 316LN stainless steel specimens tested at 25℃ and 600℃ were investigated by X-ray diffraction. Thin foils in the region below fatigue fracture surface were extracted in a transmission electron microscope at 200KV to investigate the dislocation structure of fatigue plastic zone. The regions observed in the TEM corresponded to a zone of 200-300 μm depth from the fracture surface.

3. RESULTS AND DISCUSSION

3.1 fatigue crack growth tests

Fatigue crack growth rates(da/dN) of 316LN stainless steel as a function of ΔK at 25℃ in air are shown in Fig. 1. The slope of the log da/dN versus log ΔK curve is macroscopically linear and fits the Paris equation[6]. But the scattering ranges of da/dN at low ΔK are much wider than those at high ΔK. This fact represents that the cracks grow at various rates, and the growth rates are very dependent on microscopic structure in the materials at low ΔK.

The fatigue crack growth rate(da/dN) of 316LN and 316L stainless steel vs. fatigue cycles at 300℃ are shown in Fig. 2 to compare the resistance to fatigue crack growth. Above da/dN of 2×10^{-4} mm/cycle, it takes much longer cycles to failure in 316LN stainless steel than in 316L stainless steel. This fact seems to reflect that the critical rate for unstable fatigue crack growth is higher in 316LN stainless steel than in 316L stainless steel. 316LN stainless steel shows more resistant behavior to fatigue crack growth than 316L stainless steel does.

Fatigue crack growth rates(da/dN) of 316L and 316LN stainless steel as a function of stress intensity range(ΔK) at 600℃ were shown in Fig. 3. As ΔK increases, fatigue crack growth rate increase more rapidly in 316L stainless steel than does in 316LN stainless steel. It is clear that the resistance to fatigue crack growth of 316LN stainless steel is better than that of 316L stainless steel also at 600℃.

The fatigue crack growth rates increase as temperature increases as shown in Fig. 4. The fatigue crack growth rates of 316L and 316LN stainless steel were shown as a function of (10^3/Temperature) for various stress intensity ranges(ΔK =22MPam$^{1/2}$, 30MPam$^{1/2}$, 40MPam$^{1/2}$). As temperature increase, the fatigue crack growth rate increase with acceleration. The difference of fatigue crack growth rate between 300℃ and 600℃ is significant compared with that between at 25℃ and at 300℃. This fact means that the fatigue degradation mechanism can be affected by high temperature oxidation or by the decrease of material strength at high temperature. And it can also be confirmed in Fig. 4 that the fatigue crack growth resistance of 316LN steel is improved with the addition of nitrogen.

The fatigue crack growth rates of 316LN stainless steel at 600℃ as a function of stress intensity range at the frequencies of 1 Hz and 0.1 Hz were compared in Fig. 5. The fatigue crack growth rates at the frequency of 0.1 Hz were increased with the value of about 5 fold in the stress intensity ranges from 20 $MPam^{1/2}$ to 40 $MPam^{1/2}$. It can be considered that the high temperature creep mechanism influences the fatigue crack process.

The fatigue crack growth rate of 316LN stainless steel at 600℃ increases as the R ratio increase as shown in Fig 6. Especially in the stress intensity ranges between at 20 $MPam^{1/2}$ and 30 $MPam^{1/2}$, the fatigue crack growth rate(da/dN) increased significantly for R=0.3 and 0.5. The significant increase can be related to the crack closure effect in those stress ranges.

The fatigue crack growth resistance of the specimen with large grain(126μm) is better than that of the specimen with small grain(86μm). It was shown in Fig. 7 and Fig. 8 that the crack growth rate of the specimen of smaller grain size(86μm) is faster than that of the larger specimen(126μm). The fatigue crack growth rate of the material with smaller grain size is about 2 fold faster than that of the material with larger grain size. It is considered that grain size of material is significant factor which determine the crack growth rate of 316LN stainless steel.

3.2 fatigue creep test: comparison of 316L and 316LN stainless steel

Maximum stresses for two 316L stainless steel(0.04% N, 0.1% N) during fatigue-creep tests as a function of fatigue cycles were shown in Fig. 9. Maximum stress increase to a saturated value during the first stage of the test and then maintain at a constant value to failure time. Maximum stress of 316LN stainless steel(0.1% N) is higher than that of 316L stainless steel(0.04% N) and the cycles to failure of 316LN stainless steel(0.1% N) is larger than that of 316L stainless steel(0.04% N). The cycles to failure is 603 cycles for 316LN stainless steel(0.1% N) and 534 cycles for 316L stainless steel(0.04% N). The fatigue life of about 10% increase in 316LN stainless steel(0.1% N) was shown compared with that of 316L stainless steel(0.04% N).

3.3 microstructure of fatigue plastic zone

X-ray diffraction patterns for the fracture surfaces, which were formed during fatigue crack growth tests for 316L and 316LN stainless steels at 25℃ and 600℃, were shown in Fig. 10. Peaks for diffraction planes of martensite phase, (110), (211) appear in the fracture surface of 316L and 316LN stainless steel after fatigue crack growth tests at 25℃ and 600℃. It can be considered that there is no significant difference in the amount of strain induced martensitic transformation in both 316L and 316LN stainless steel. There seems some strengthening effect induced by martensite transformation. However, it seems that strain induced martensitic transformation is not critical factor for the difference of the fatigue crack growth rates between 316L and 316LN stainless steel.

Dislocation structures in fatigue plastic zone of 316L and 316LN stainless steel tested at 25℃ are shown in Fig. 10. The figures are for the fatigue plastic zones below fracture planes at ΔK = 35 $MPam^{1/2}$. The dislocation structure of 316L stainless steel shows cellular arrangement of dislocation tangles, whereas the dislocation structure of 316LN stainless steel shows planer arrangement. The significant difference of 316L and 316LN stainless steel during fatigue crack growth process is the dislocation structure in the cyclic plastic strain zone. The planar arrangement of dislocation means that it is more difficult to cross slip in 316LN stainless steel than in 316L stainless steel. So it is considered that the improvement of

316LN stainless steel in the fatigue crack growth resistance is attributed to the difficulty in cross slip in 316LN stainless steel.

4. CONCLUSION

1) Nitrogen added 316LN stainless steel(0.14 % N) has a better fatigue crack resistance than 316L stainless steel does at 600℃.
2) The fatigue crack growth rates of 316LN stainless steel increase as temperature, frequency and R ratio increases.
3) 316LN stainless steel with larger grain size(126μm) has a better fatigue resistance than 316L stainless steel with smaller grain size(86μm) does at 600℃.
4) Nitrogen added 316LN stainless steel(0.1% N) has a longer fatigue-creep life than 316L stainless steel(0.04% N) does at 600℃.
5) The better fatigue crack growth resistance of 316LN stainless steels considered to be attributed to the planer slip character in the fatigue plastic zone.

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Table 1. Chemical compositions of 316L and 316LN stainless steel

Element(%)	C	Ni	Cr	Mn	P	S	Si	Mo	N
316L	0.020	11.21	17.38	1.86	0.027	0.0054	0.51	2.36	**0.038**
316LN	0.018	11.23	17.58	1.67	0.021	0.0008	0.46	2.79	**0.14**

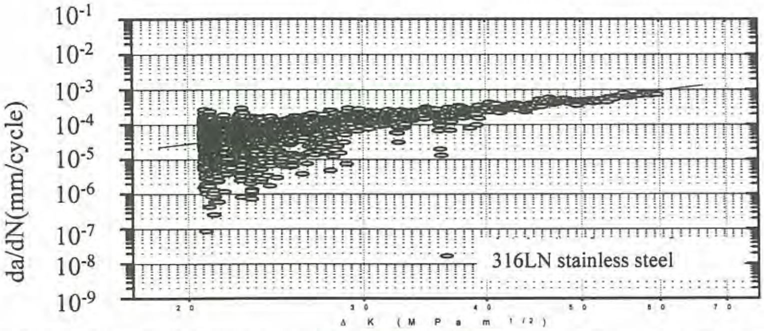


Fig. 1 Fatigue crack growth rate of 316LN stainless steel at 25℃ as a function of Δ K at 25℃.

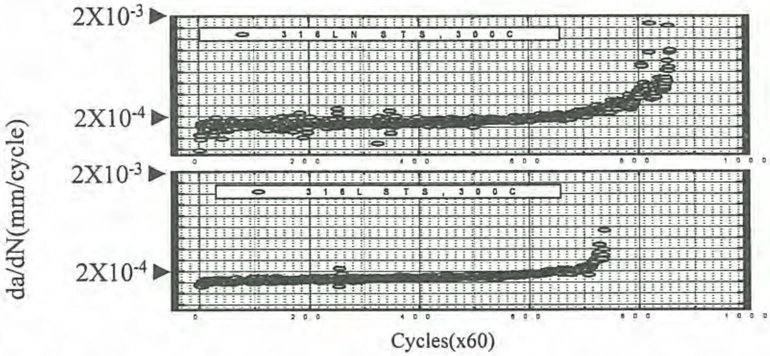


Fig. 2 Fatigue crack length of 316L(0.04% N) and 316LN(0.14% N) stainless steel as a function of fatigue cycles at 300℃.

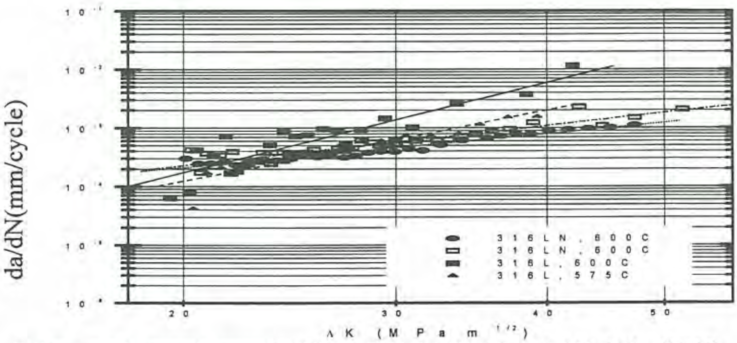


Fig. 3. Fatigue crack growth rates(da/dN) of 316L(0.04% N) and 316LN(0.14% N) stainless steels as a function of Δ K at 600℃.

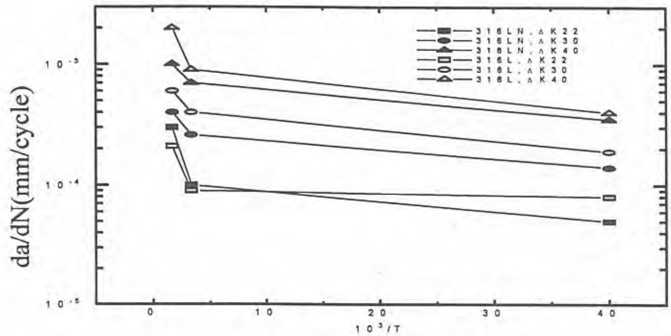
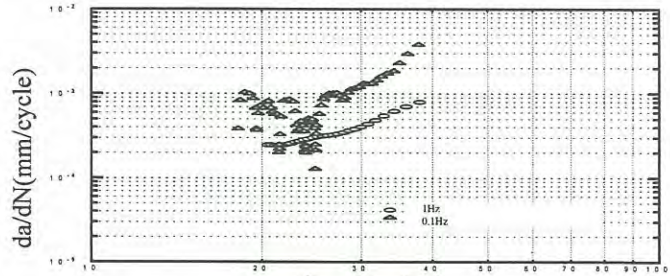
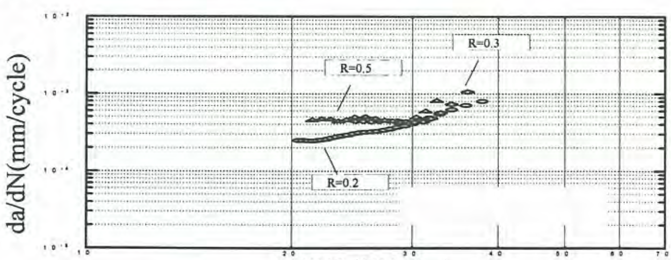


Fig. 4. Temperature dependence on the fatigue crack growth rate of 316LN stainless steel.



Δ K(MPam1/2)

Fig. 5 Effect of frequency on the fatigue crack growth rate of 316LN stainless steel at 600℃.



Δ K($MPam^{1/2}$)

Fig. 6. Effect of load ratio on fatigue crack growth rate of 316LN stainless steel at 600℃.

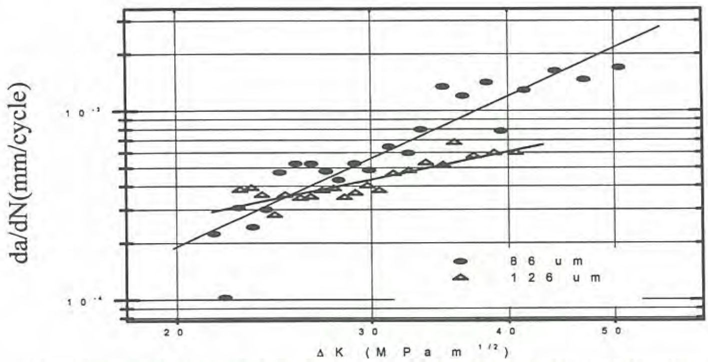


Fig. 7. Fatigue crack growth rate(da/dN) of 316LN stainless steel with different grain size as a function of Δ K at 600℃.

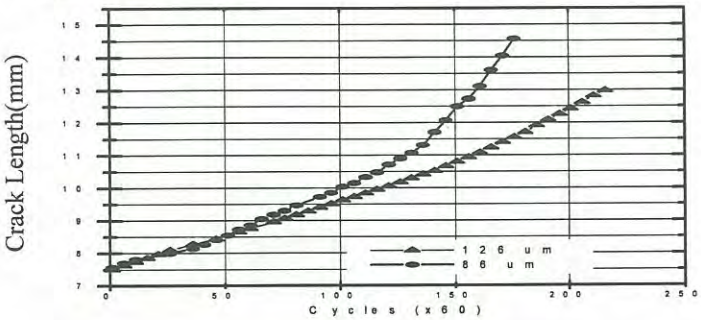


Fig. 8. Fatigue crack length of 316LN(0.14% N) stainless steel with different grain size as a function of fatigue cycles at 600℃.

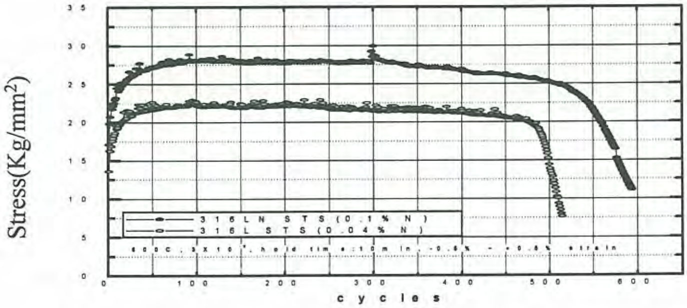


Fig. 9. Maximum stress vs. fatigue-creep cycle during fatigue-creep test of 316L(0.04% N) and 316LN(0.1%N) stainless steels.

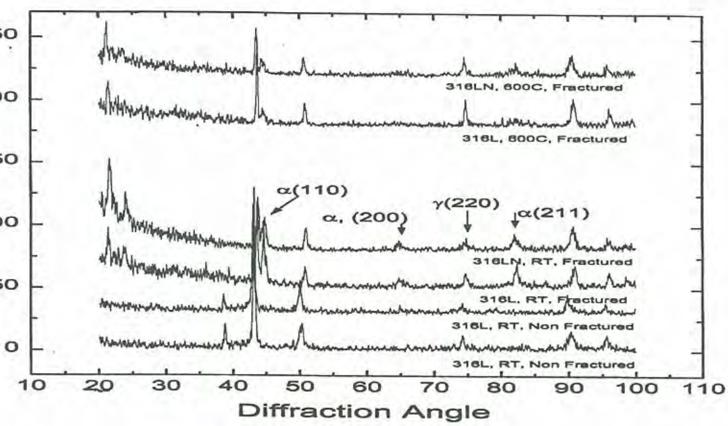


Fig.10 Results of X-ray diffraction analysis for the fatigue fracture surfaces of 316L and 316LN stainless steels.

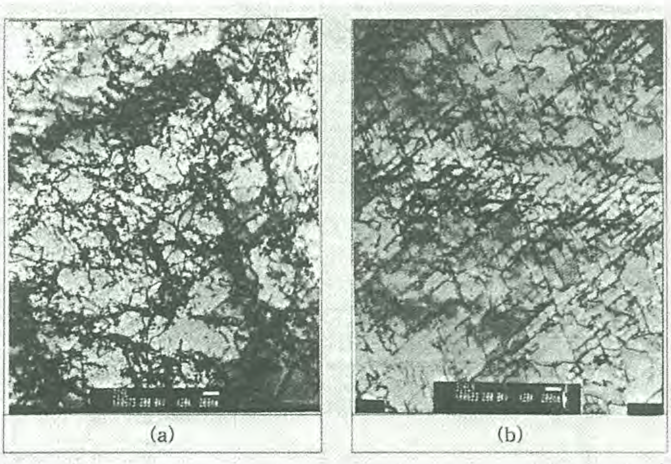


Fig. 11 Dislocation structures at the cyclic plastic zones at fatigue crack tip of stainless steel (a:316L, b:316LN).