Proceeding of the Korean Nuclear Society Autumn Meeting
Taejon, Korea, October 2000

Fatigue Crack Nucleation of Type 316LN Stainless steel

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Abstract

Low cycle fatigue (LCF) life decreases drastically with increasing temperature but increases with the addition of nitrogen at room and high temperatures. The effect of nitrogen on LCF life may be related to crack nucleation at high temperatures in austenitic stainless steel because the fraction of crack nucleation in LCF life is about 40%. The influence of nitrogen on the crack nucleation of LCF in type 316LN stainless steel is investigated by observations of crack population and crack depth after testing at 40% of fatigue life. Nitrogen increases the number of cycles to nucleate microcracks of 100μm but decreases the crack population.

1. Introduction

The reactor vessel and piping of liquid metal reactors (LMR) are subjected to repeated thermal stresses as a result of temperature gradients which are induced by heating and cooling during starts-ups and shut-downs. Therefore, resistance to LCF at high temperature is an essential requirement in the design of LMR components which operate at 550°C. Type 316LN stainless steel is a prospective structural material for LMR because nitrogen is known to be beneficial to LCF resistance and decreases the precipitation of carbides.

Fatigue life is composed of crack nucleation and crack propagation. So, the increase of fatigue life by the addition of nitrogen may be related to the behavior of crack nucleation and/or crack propagation. Dhers and Vogt et al. [1,2] reported that nitrogen decreased fatigue crack growth rate at room temperature in type 316LN stainless steel with two different nitrogen contents. Although Maiya [3] reports that crack nucleation stage has a large portion in LCF life, the influence of nitrogen on crack nucleation in LCF life has not been clear yet. The purpose of this study is to investigate the influence of nitrogen on the crack nucleation. Maiya and Busch[4] defined the crack depth for crack nucleation of LCF as 100μm from surface in the view point of microstrucrure. In this study, the testing cycles was chosen as a constant fraction (40%) of LCF life tested at 1% total strain because the crack depth were about 100μm at this fraction.

2. Experimental procedure

Laboratory ingots containing different levels of nitrogen were prepared by vacuum induction melting. The chemical compositions are given in Table 1. Alloys were solution-treated at 1100°C for 1 hour and water quenched. Grain size was 100μm for N04 specimens and 47μm for N10 specimens. Tensile and LCF test specimens were taken as rolling direction and machined to cylinder with 4 mm diameter, 25mm gage length for tensile and 7 mm diameter, 8 mm gauge length for LCF.

Table 1. Chemical composition of experimental melts (wt%)

Spec. ID	C	Si	Mn	Ni	Cr	Mo	N
N04	0.018	0.67	0.95	12.21	17.78	2.36	0.04
N10	0.019	0.70	0.97	12.46	17.23	2.38	0.10

Tensile tests were carried out under the displacement control. LCF tests were carried out up to 40% of fatigue life in air environment under fully reversed axial strain control mode. A strain gauge was directly attached to the shoulder of the specimen. The waveform was triangular with a total strain of 1.0% and the test temperature was in the range of room temperature~600°C and temperature was maintained constantly within ±2°C during the period of the test. All specimens were held at the test temperature for 1 hour before starting the test. The strain rate was 2×10^{-3}/s for tensile and LCF tests.

Cycles for crack nucleation test were 40% of LCF life at each temperature. For the observation of cracks a gauge length part was cut from the specimens after testing 40% of LCF life. Crack population on the surface of specimens was observed using scanning electron microscopy (SEM) at each 45° rotation. Crack depths from the surface were observed using the optical microscope after cutting the gauge length longitudinally and etching the surface with 8% nitric acid and 54% hydrochloric acid. The maximum crack depth from the surface was defined as the longest crack of many cracks nucleated from the surface to matrix. Striation spacing was measured using SEM from the surface of specimens failed by LCF test.

3. Results and Discussion

Yield, ultimate tensile stress, and elongation increased with the addition of nitrogen as shown in Fig.

1. This may be due to solid solution, grain size refinement, and short range order (SRO). Elongation decreased, was the minimum at 400°C, and increased with increasing temperature. This behavior of elongation is one of many evidences for dynamic strain aging (DSA) because DSA decreases ductility. Elongation did not change with the addition of nitrogen. In Fig. 2, The temperature range for DSA was investigated with strain rate and temperature. The temperature range for DSA was 350~725°C at $2x10^{-3}$/s in tensile test.

The effect of nitrogen on fatigue life was investigated with temperature at total strain of 1.0% in Fig. 3. Fatigue life was almost same up to 300°C but decreased drastically with increasing temperature above 300°C. Fatigue life increased with the addition of nitrogen at room temperature~600°C. Saturation stress with temperature was shown in Fig. 4. From the tensile test, yield and ultimate tensile strength decreased with the increase of temperature but in the fatigue test, tensile strength increased with the increase of temperature. So, it is considered that DSA occurs during fatigue test at the temperature range from 300°C to 600°C because it is known that DSA increases strength.

Tsuzaki et al.[5] observed that serrations began in the saturated stress stage of fatigue process under various strain rate and temperature in type 304 stainless steel. The critical temperature for the onset of serrations during fatigue deformation was much lower than that during monotonic tensile deformation with various strain rate and temperature range. From the Tsuzaki's result, the temperature range for the decrease of fatigue life was consistent with the temperature range for DSA. It is considered that nitrogen decreased DSA and increased fatigue life at high temperature because DSA contributes to the decrease of fatigue life at high temperature. In addition, Nilsson[6] reported that the increase of fatigue life by the addition of nitrogen was ascribed to the planar slip mode, which is due to short range order (SRO) formed by the strong interaction of chromium and nitrogen .

Fatigue cracks are usually nucleated at a free surface. The mode of crack nucleation is dependent on the test conditions, such as strain range, test temperature, and slip character. At low strain amplitude the applied plastic strain is concentrated in a few persistent slip band (PSB), which leads to extrusion-intrusion topography and microcrack formation along the slip bands. Twin boundary is also a favorable site for cracking in f.c.c. metals which contain an annealing twin. At high strain amplitude grain boundaries become the preferred sites for crack nucleation. The stress concentration induced by the strain incompatibility across the interface enhances grain boundary cracking. Several types of stress concentrations at high strain amplitudes are induced at surface rumpling, step formation at grain boundaries, impinging slip band at the interfaces and precipitation. The preferred sites for crack nucleation in this study were observed at grain boundary, twin boundary and slip band as shown in Fig. 5, but most of the cracks nucleated at the grain boundary.

Crack population on the surface after test at 40% of fatigue life was shown in Fig. 6. Crack population was almost constant up to 500°C and increased at 600°C. Bressers[7] reported the crack density increased with the cycle number at 600°C and 800°C in Alloy 800H. In that material, DSA stops operating at a temperature of approximately 650°C. There was a concomitant increase in the number of cycles to initiate micocracks, an appreciably lower crack density and a longer overall life at 800°C as compared to 600°C. Crack population increased at 600°C because DSA occurred actively about 600°C. The increase of crack population at 600°C in this study is consistent with Bressers's result. Crack population decreased with the addition of nitrogen. This is considered that the planar slip produced by nitrogen gives slip reversibility not to be concentrated the strain at grain boundary or the planar slip distributes the strain into the matrix in the high nitrogen alloyed steels.

Maximum crack depth was larger for N04 than for N10 at room temperature but almost same at high temperature as shown in Fig. 6. Maximum crack depth was almost 100μm at high temperature and did not change greatly with the addition of nitrogen except room temperature. The fraction of crack nucleation producing 100μm crack was to be defined about 40% of fatigue life for N04 and N10 at this test condition but the cycles for crack nucleation increased with the addition of nitrogen. Therefore, it is considered that nitrogen decreased crack nucleation as long as Maiya's definition for crack nucleation is accepted.

4. Conclusions

Strain-controlled LCF was conducted up to 40% of fatigue life from room temperature to 600°C to investigate crack nucleation behaviors in type 316LN stainless steel. The results are as follows;

1. LCF life increases with the addition of nitrogen.
2. Crack population on the surface increases at 600°C which DSA is the most active but decreases with the addition of nitrogen.
3. Maximum crack depth at 40% of fatigue life is about 100 μm. Maximum crack depth does not change but cycles for crack nucleation increases with the addition of nitrogen at high temperature.
4. Nitrogen decreases the crack nucleation and contributes to the increase of fatigue life at high temperature.

Acknowledgements

This work was conducted by Nuclear Materials Technology Development Team of Korea Atomic Energy Research Institute as a part of Nuclear R&D program of Ministry of Science and Technology in Korea.

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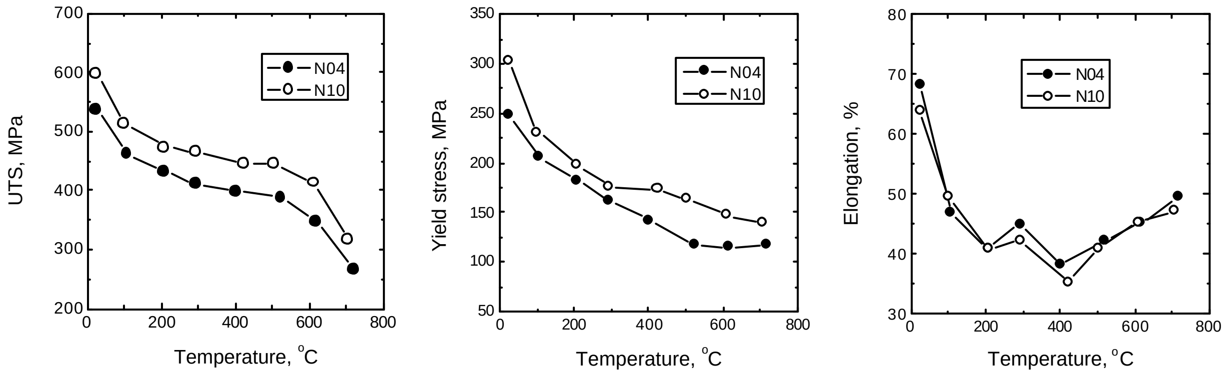
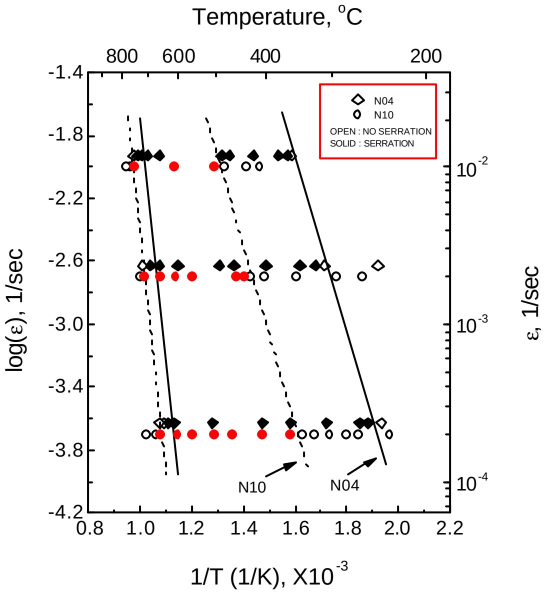


Fig. 1. Yield stress with temperature and nitrogen content.



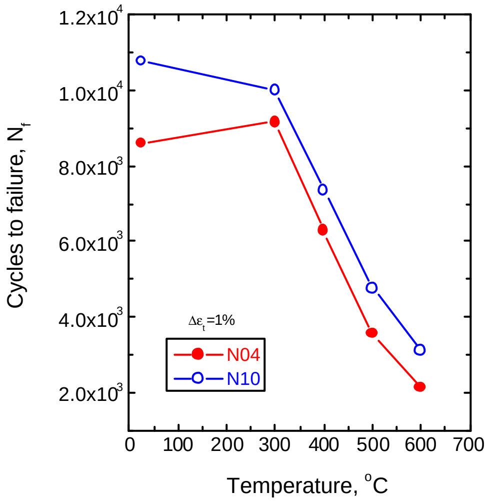


Fig. 2. Elongation with temperature and nitrogen content.

Fig. 3. Low cycle fatigue life with Nitrogen content and temperature.

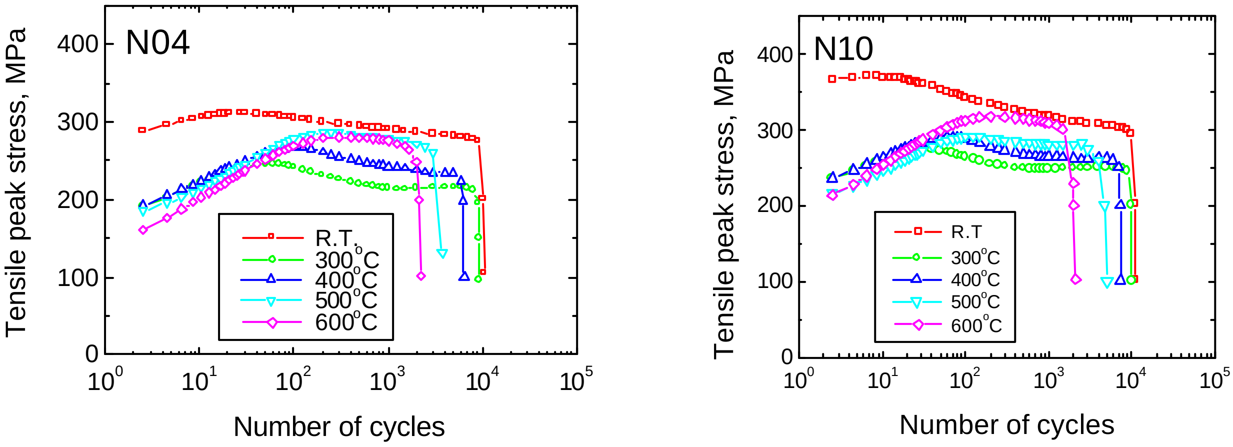
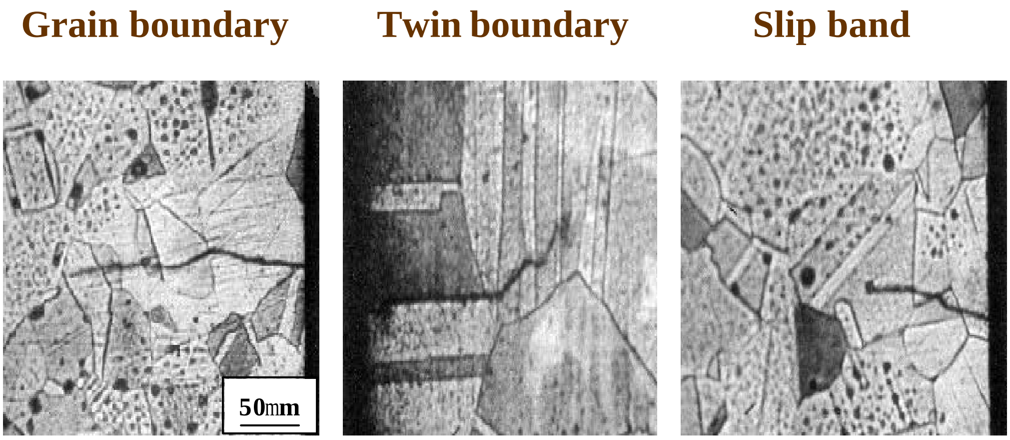


Fig. 4. Saturation stress with temperature tested at De$_t$=1%.



Grain boundary

Twin boundary

Slip band

Fig. 5. Crack nucleation sites.

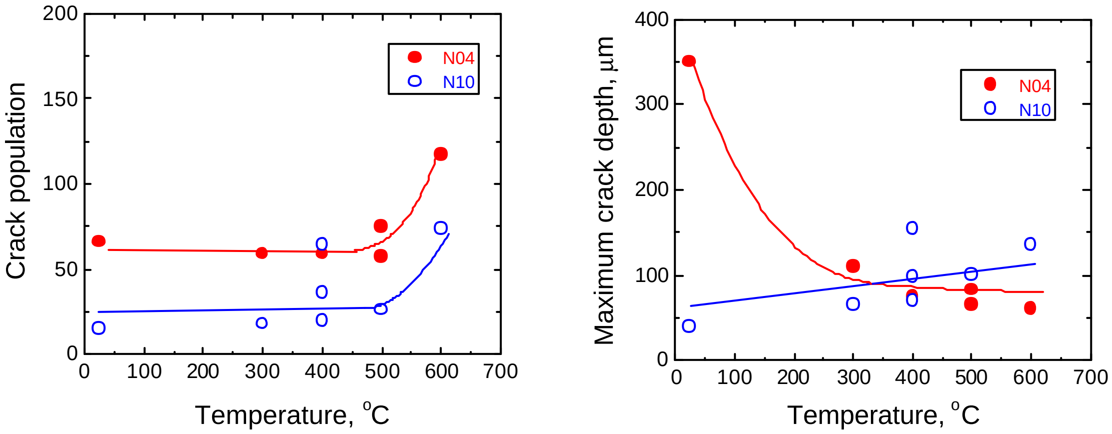


Fig. 6. Crack population and maximum crack depth with temperature and nitrogen content.