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Fatigue Characteristics of STS 304 Stainless Steel for LNG Storage Tank at Low Temperature

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1. Introduction

In the engineering applications, many metallic structures operate below the room temperature, such as liquefied gas tank, space shuttles, nuclear fusion reactors and superconducting machinery [1]. In order to ensure the safety of these structures and to prevent fatigue failure under service conditions, it is of practical importance to predict accurately the fatigue life of components applied at low temperatures.

Among the structural materials having high toughness and high fatigue strength at room and cryogenic temperatures, Type 304 stainless steel is widely used in cryogenic structures due to favorable mechanical properties, service history and availability. In the cryogenic applications such as a liquefied natural gas (LNG) storage tanks, the material will experience thermal cycling over a range of room temperature to 111K (the service temperature of LNG tanks). And cracks already exist, or are assumed to exist, due to manufacturing and fabrication defects. In such cases, the life of the structure is determined solely by the crack growth rate, and a specific knowledge of fatigue crack growth rates (da/dN) is essential for accurate fatigue life predictions.

In this study, the constant amplitude fatigue crack growth tests of the cold-worked STS 304 stainless steel, developed as a material for the membrane of LNG storage tank, were conducted at a temperature range from 293K to 111K. The effects of a stress ratio and a crack orientation on the fatigue crack growth rate were estimated experimentally. Fractographic examinations were also performed to reveal the differences of the fatigue crack growth characteristics at room and low temperatures.

2. Experimental procedure

2.1 Material and apparatus

The material used in this study was a 2 mm thick plate of STS 304 stainless steel produced by POSCO. Its chemical composition and mechanical properties are shown in Table 1 and 2. Fatigue tests at room and low temperature were conducted on MTS, 100 kN capacity, with a cryostat. The specimens are installed into the clevises, and liquid nitrogen is poured into the chamber to cool the specimen. All the tests began after the temperature has stabilized at 111, 193 and 273 K. The testing incorporates a personal computer to enable digital data acquisition and plot the fatigue crack growth rate (da/dN) versus the stress intensity factor range (ΔK) graph during the tests.

Table 1. Chemical compositions (*wt*%)

C	Mn	P	S	Si	Cr	Ni
0.05	1.2	0.021	0.008	0.41	18.02	8.6

Table 2. Mechanical properties

Temp. (K)	0.2% YS (MPa)	UTS (MPa)	Elong. (%)
293	306.8	720.5	63.2
193	496.9	1162.5	32.7
111	550.7	1495.0	28.9

2.2 Specimens and fatigue tests

The compact tension (CT) specimens were 2 mm thick and 40 mm wide, and three identical specimens were prepared for each test conditions. The notch was machined in the *L-T* and *T-L* orientations, as defined in ASTM E399-90. The constant amplitude fatigue tests were performed with two stress ratios ($R = \sigma_{min}/\sigma_{max}$) of 0.1 and 0.5, and a 6Hz sine waveform. Crack length was measured by a compliance method using a clip-on gage mounted at the specimen edge. The fatigue crack growth rates were estimated by a seven point incremental polynomial method [2].

3. Results and discussion

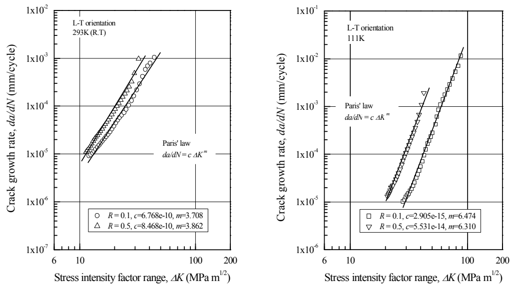
3.1 Fatigue crack growth behavior

As demonstrated by Paris et al. [3], a fatigue crack growth rates (da/dN) can usually be described as power-law function of the stress intensity factor range (ΔK)

$$da/dN = C(\Delta K)^m \tag{1}$$

where C and m are material constants that depend on environment and test variables.

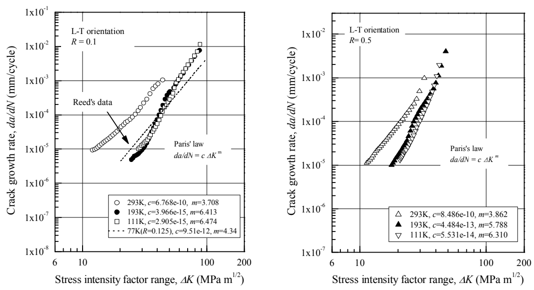
The fatigue crack growth rates at room (293 K) and 110 K are plotted against ΔK on logarithmic coordinates in Fig. 1. At equivalent ΔK values, da/dN increases with an increase in a stress ratio (R) over the testing temperature. This trend is the same as the test results reported by Tshegg et al. [4] and Liaw et al. [5]. The effect of stress ratio on fatigue crack growth rate is more explicit at low temperatures than at room temperature. There is little or no difference in *da*/*dN* in the L-T and T-L orientations.



(a) 293 K (b) 111 K

Fig. 1 The effect of stress ratio on the fatigue crack growth rate

Fatigue crack growth data at 293, 193 and 111 K are presented in Fig. 2. In Figure 2(a), the dot line is the test results of SUS 304 stainless steel tested at 77 K by Reed et al. [6]. The rates at low temperatures are lower than at room temperature. Previous researchers indicated that this trend is attributed to the extent of strain-induced martensitic transformation at the crack tip [4,7]. At lower ΔK region, the fatigue crack growth resistance is higher at low temperatures than at room temperature. The temperature dependence of fatigue crack growth resistance is gradually vanished with an increase in stress intensity factor range (ΔK), which correlates with a decrease in fracture toughness with decreasing temperature.

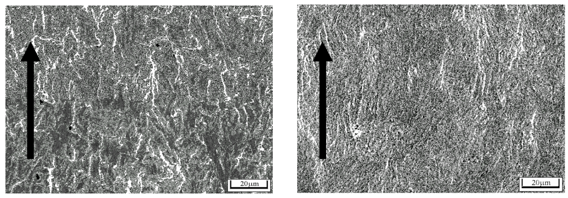


(a) R=0.1 (b) R=0.5

Fig. 2 The effect of low temperature on the fatigue crack growth rate

3.2 Fractography

Micrographs taken with a SEM are shown in Fig. 3, which are typical examples for the fatigue fracture appearance tested at 293 and 111 K. The fracture surface at 111 K is characterized by a very smooth appearance. Therefore, it is found that the differences of the fatigue crack growth behavior at room and low temperatures result in the crack closure and the strengthening due to the martensitic transformation.



(a) 293K (b) 111K

(※Arrow indicates a macrocrack growth direction.)

Fig. 3 SEM micrographs of the fracture surfaces

($\Delta K \approx 21.5 \mathrm{MPa\ m}^{1/2}$)

4. Conclusion

The fatigue crack growth behavior of the cold-rolled STS 304 stainless steel developed for a membrane material of LNG storage tank was examined experimentally at 293K, 193K and 111K. The following conclusions are made.

1. The effect of stress ration (*R*) on fatigue crack growth rate (*da*/*dN*) is more explicit at low temperatures than at room temperature. There is little or no difference in *da*/*dN* in the L-T and T-L orientations. The resistance of fatigue crack growth at low temperatures is higher than at room temperature, which is attributed to the extent of strain-induced martensitic transformation at the crack tip.
2. The temperature dependence of fatigue crack growth resistance is gradually vanished with an increase in stress intensity factor range (ΔK), which correlates with a decrease in fracture toughness with decreasing temperature.
3. Fractographic examinations reveal that the differences of the fatigue crack growth characteristics between room and low temperatures result in the crack closure and the strengthening due to the martensitic transformation.

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