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FATIGUE CRACK GROWTH PROPERTIES OF TYPICAL PRESSURE VESSEL STEELS AT HIGH TEMPERATURE

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Abstract

Fatigue failures often take place in high temperature pressure vessels and equipment because of fluctuation of pressure and temperature. Fatigue crack growth properties of materials at high temperatures are very important for safety assessment of high temperature equipment. A series of fatigue crack growth tests were carried out, and fatigue crack growth rates were determined at 25~500℃ for three typical steels for Chinese pressure vessels $2.25Cr1Mo$, $2.25Cr1MoV$ and 16MnR. The laws of fatigue crack growth of three materials at different temperatures and the effect of temperature on fatigue crack growth rates were studied.

The results show that the fatigue crack growth laws of $2.25Cr1Mo$ are nearly the same as that of $2.25Cr1MoV$ at high temperature. The crack growth rates increase with the temperature for both materials. The exponent *n* for Paris law changes little at different temperatures, while constant *C* for Paris law changes with the temperature. Both the exponent *n* and constant *C* for Paris law change with temperature. The fatigue cracks of 16MnR propagate at 150℃ and 300℃ more slowly than at room temperature and 425℃. The fatigue crack growth rate at 425℃ is the highest for temperature range of 25-425℃. The fatigue cracks propagate mainly transgranularly at room temperature, while they propagate mainly intergranularly at high temperature.

Key Words: fatigue crack growth rate, high temperature, fatigue crack growth mechanism, pressure vessel steels

INTRODUCTION

Many pressure vessels and piping in nuclear power plants, power plants and petrochemical plants are operated at high temperature. Stresses in these equipment and structures often fluctuate because of change of pressure or temperature and will result in fatigue failures and fatigue crack propagation. Fatigue of high temperature equipment and structures is a complicated problem, which is related in temperature, stress, metallurgical process, corrosion environment, load history and so on. Research on fatigue crack propagation of typical materials at high temperature is important and practical for safety assessment and management of high temperature equipment and structures.

$2.25Cr1Mo$ and $2.25Cr1MoV$ are heat resistant low alloy steels, which are used in hydrogenation reactors. Resistance of hydrogen induced corrosion of 2.25Cr1MoV is increased greatly, as small amount of vanadium is

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added into the steel [1]. 16MnR steel is one of the C–Mn steels in significant use for pressure vessels in China. Almost one half of the pressure vessels for medium–low pressure are made of 16MnR steel. Fatigue failures often take place in high temperature pressure vessels and equipment because of fluctuation of pressure and temperature. Fatigue crack growth properties of materials at high temperatures are very important for safety assessment of the high temperature equipment. Fatigue crack growth rates of 16MnR, 2.25Cr1Mo and 2.25Cr1MoV steels at room temperature have been studied by many researchers [2-3]. Many fatigue test data are reported for these two materials. However, test and study of the fatigue properties of the materials at from room temperature to 500℃ for 2.25Cr1Mo and 2.25Cr1MoV are not enough. Fatigue crack growth properties of 16MnR, 2.25Cr1Mo and 2.25Cr1MoV steels at elevated temperatures should be studied. In this paper, a series of fatigue crack growth tests were carried out, and fatigue crack growth rates were obtained at 25~500℃ for 16MnR, 2.25Cr1Mo and 2.25Cr1MoV steels. The laws of fatigue crack growth of three materials at different temperatures and the effect of temperature on fatigue crack growth rates were studied.

MATERIALS AND SPECIMENS

Test Materials

The chemical compositions and mechanical properties of the three metals are shown in Tables 1, 2, 3 and 4.

Table 1 Chemical Compositions of the materials (wt%)

Material	C	Mn	Si	S	P	Cr	Ni	Mo	Ti	Ca	Cu	V	Nb
16MnR	0.15	1.54	0.3	0.01	0.02	/	/	/	/	/	/	/	/
2.25Cr1Mo	0.147	0.54	0.14	0.0038	0.0087	2.22	/	0.90	/	/	/	/	/
2.25Cr1MoV	0.147	0.54	0.007	0.0039	0.0087	2.22	0.14	0.90	0.035	0.010	0.12	0.26	0.04

Table 2 Mechanical Properties of 2.25Cr1Mo

Temperature (℃)	Young's modulus (10^5 MPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction in area (%)
25	2.0035	478.00	603.00	26.70	79.26
200	1.9229	407.50	517.00	19.20	78.35
420	1.8763	387.00	497.50	19.04	74.84
500	1.7353	359.50	457.00	21.14	80.41

Table 3 Mechanical Properties of 2.25Cr1MoV

Temperature (℃)	Young's modulus (10^5 MPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction in area (%)
25	2.0132	568.50	670.00	25.18	76.83
200	1.9803	424.50	592.50	22.10	76.08
350	1.8680	378.00	566.50	21.18	78.13
500	1.6926	349.50	511.00	24.50	78.18

Table 4 Mechanical Properties of 16MnR

Temperature ℃	25	150	300	425
Young's Modulus (10^5 MPa)	2.09	2.05	1.93	1.80
Yield strength σ_y (MPa)	370	340	300	280

Specimens

The test specimens are CT specimens, being in accordance with the ASTM E647-2000 Standard[5]. The orientation of the crack plane of the specimens is T-L, i.e., the direction normal to the crack plane is the width direction of the plate and the expected direction of crack propagation is coincident with longitudinal direction of the plate. The dimensions of the specimen are shown in Fig.1.

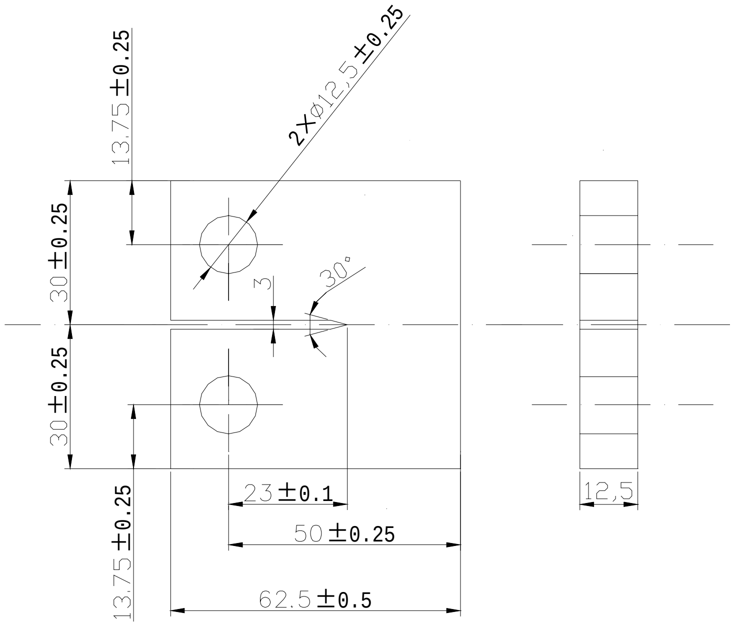


Fig.1. Sketch of CT specimens, Dimensions in millimeter

FATIGUE TESTS

The fatigue pre–crack was produced at room temperature by the ΔK-decreasing fatigue test procedure. The length of the fatigue pre–crack is 2-3mm. All fatigue crack growth tests were done on a computer controlled servohydraulic material testing machine (Model EHF-ED250kN-40L) manufactured by the Japanese Shamazu Company. The specimen was heated to test temperature and the temperature was held for thirty minutes, then the test began. The constant-load-amplitude procedure is used in the fatigue test. The maximum load is 6.5kN, the load ratio being 0.1 and the frequency being 10.0Hz. The load wave is a sine wave. The crack lengths under different cycles were estimated from the elastic compliance of the specimens by the displacements at load line and the loads recorded in the tests automatically by the computer of the testing machine. After the fatigue test was finished, the specimens were cleaned by ultrasonic wave. The initial crack length and final crack length were measured by a 30× microscope. The crack lengths estimated from the compliance method were verified and modified by the crack lengths measured by the BM method. The tests of three specimens of 2.25Cr1MoV at 25℃、350℃ and 500℃ were stopped when the crack propagated to certain length and the specimens were not fractured, in order that crack propagation can be checked by microscope on side face.

RESULTS AND DISCUSSION

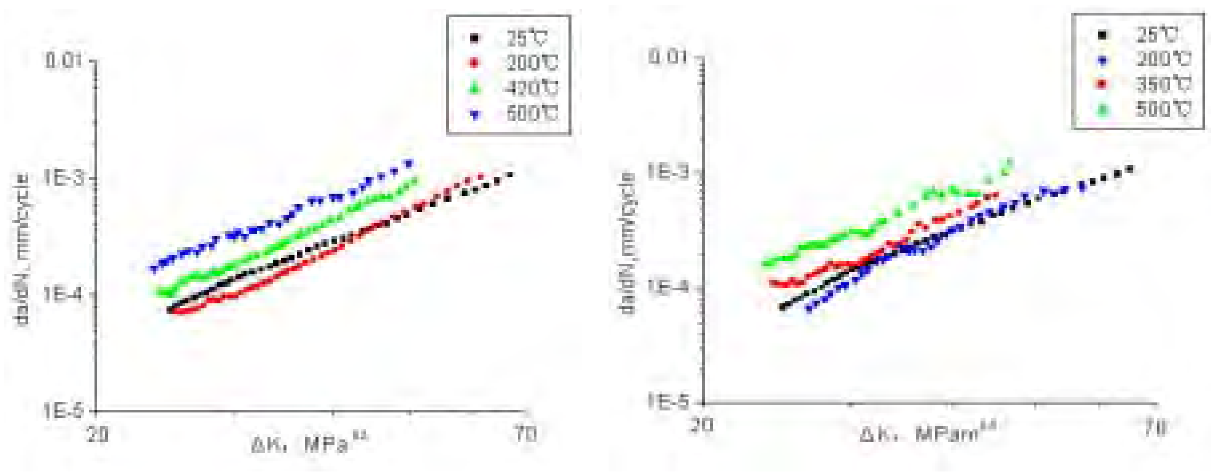
The fatigue crack growth rate da/dN was calculated by the seven successive data point incremental polynomial method suggested by ASTM E647 from test a–N data. The stress intensity factor range ΔK was calculated according to the equation given in ASTM E647. The da/dN–ΔK test data of 16MnR, 2.25Cr1Mo and 2.25Cr1MoV steels at different temperatures are given in Fig.2 to Fig.4. They are regressed according to the Paris law, shown in Table 5 and 6, $MPa\sqrt{m}$ for ΔK and *mm/cycle* for da/dN.

Table 5 Fatigue Crack Growth Rates of 2.25Cr1Mo and 2.25Cr1MoV

Temperature（℃）	Fatigue crack growth rates (Paris law)	
	2.25Cr1MoV	2.25Cr1Mo
25	$da/dN = 1.84989\times10^{-8}(\Delta K)^{2.6525}$	$da/dN = 7.9863\times10^{-9}(\Delta K)^{2.8679}$
200	$da/dN = 1.2177\times10^{-9}(\Delta K)^{3.36148}$	$da/dN = 5.11821\times10^{-9}(\Delta K)^{2.94013}$
350	$da/dN = 1.21259\times10^{-8}(\Delta K)^{2.8057}$	
420		$da/dN = 1.3246\times10^{-8}(\Delta K)^{2.812}$
500	$da/dN = 3.425\times10^{-8}(\Delta K)^{2.6903}$	$da/dN = 6.82294\times10^{-7}(\Delta K)^{2.4702}$

Table 6 Fatigue Crack Growth Rates of 16MnR

Temperature（℃）	Fatigue crack growth rates (Paris law)
25	$da/dN = 2.42327\times10^{-9}(\Delta K)^{3.3596}$
150	$da/dN = 5.7756\times10^{-9}(\Delta K)^{2.9754}$
300	$da/dN = 2.2886\times10^{-9}(\Delta K)^{3.197}$
425	$da/dN = 1.4664\times10^{-7}(\Delta K)^{2.2897}$



(a) 2.25Cr1Mo (b) 2.25Cr1MoV

Fig.2 Fatigue crack growth rate da/dN versus ΔK at different temperatures for 2.25Cr1Mo and 2.25Cr1MoV

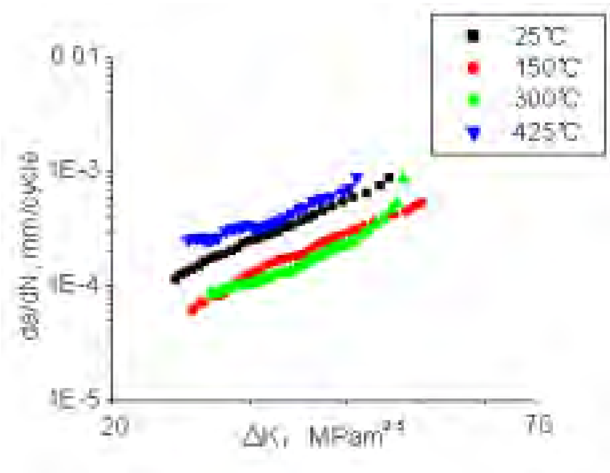


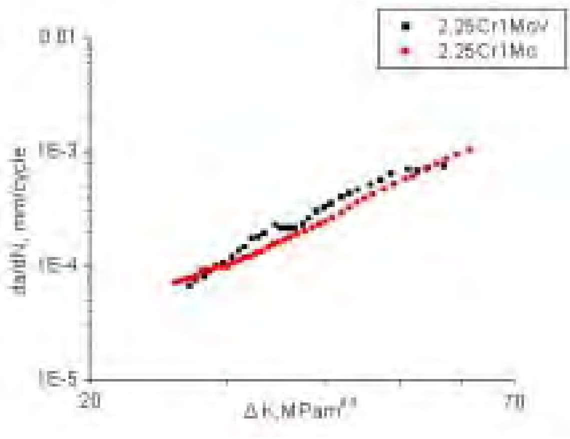
Fig.3 Fatigue crack growth rate da/dN versus ΔK at different temperatures for 16MnR

The results show that the crack growth rates increase with the temperature at temperature over 200℃ under test ΔK condition for 2.25Cr1Mo and 2.25Cr1MoV steels. The fatigue crack growth rates at room temperature and 200℃ have little difference, and the da/dN at room temperature is slightly higher than that at 200℃ under low ΔK condition. Comparison of fatigue crack growth between 2.25Cr1Mo and 2.25Cr1MoV are shown in Fig.4. The fatigue crack growth rates at the same temperature for 2.25Cr1Mo and 2.25Cr1MoV are nearly the same.

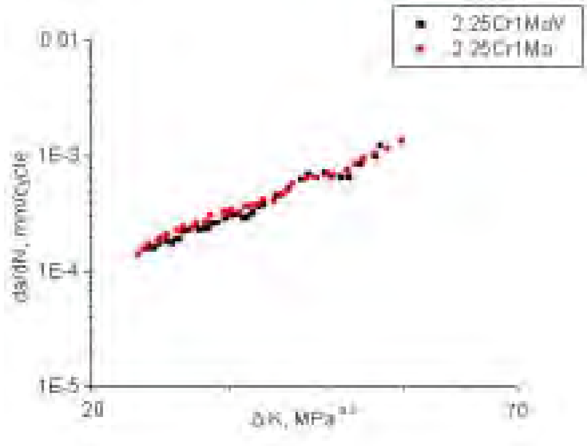
The fatigue cracks of 16MnR propagate more slowly at 150℃ and 300℃ than at room temperature and 425℃. The fatigue crack growth rate at 425℃ is the highest for the test temperature range of 25-425℃.

The fracture surfaces were observed and analyzed with SEM shown in Fig.5. The fracture surfaces at high temperatures for 2.25Cr1Mo and 2.25Cr1MoV are slightly different from each other. Fatigue surfaces are covered with oxidation materials. Shape of the oxidation material on the fracture surface of

2.25Cr1MoV at 350℃ and that of 2.25Cr1Mo at 420℃ are like sharp leaves, while the oxidation materials for both materials at 500℃ are dense and ball-shaped.

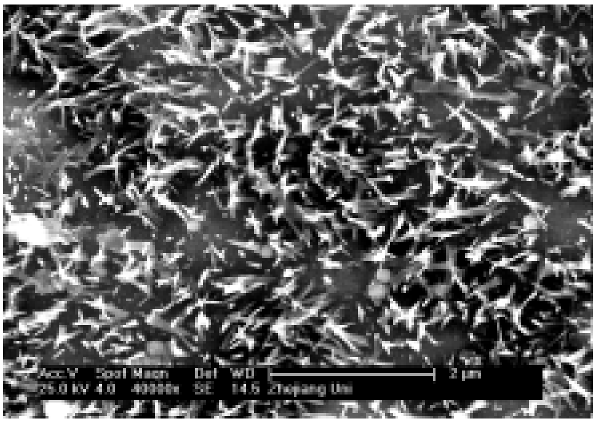


(a) at 200℃

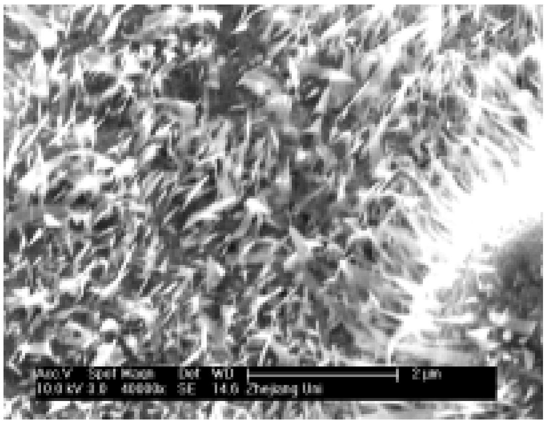


(b) at 500℃

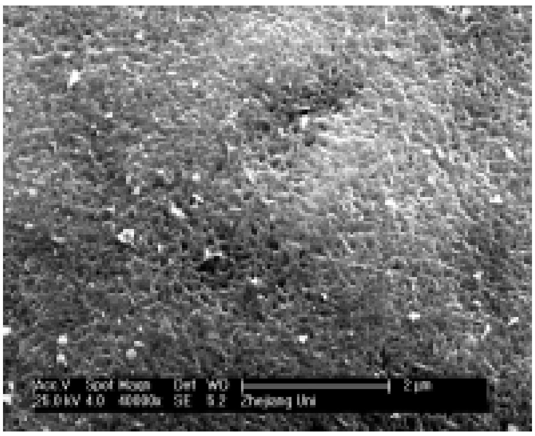
Fig.4 Comparison of fatigue crack growth rates da/dN versus ΔK for 2.25Cr1Mo and 2.25Cr1MoV



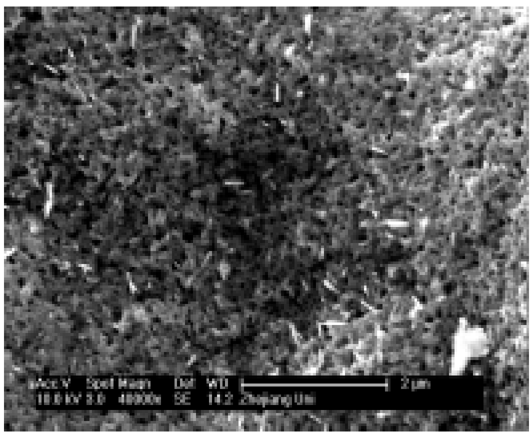
(a) 2.25Cr1MoV at 350℃



(b) 2.25Cr1Mo at 420℃



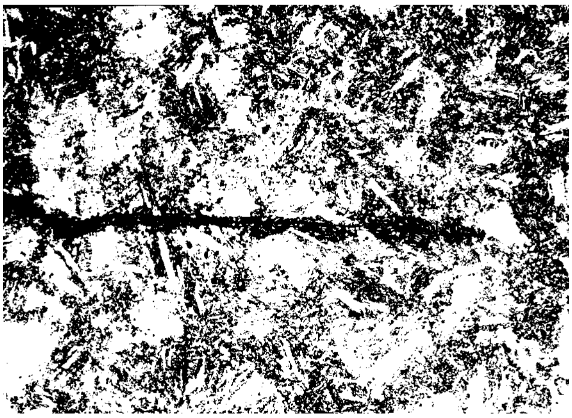
(c) 2.25Cr1MoV at 500℃



(d) 2.25Cr1Mo at 500℃

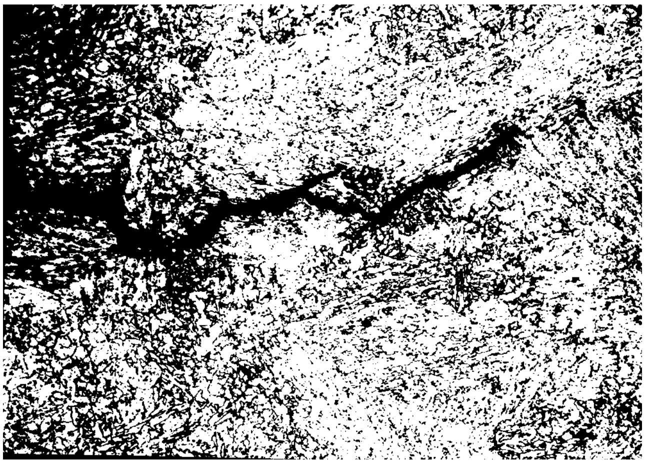
Fig.5 Fracture surface of 2.25Cr1Mo and 2.25Cr1MoV at different temperatures

Crack propagation were checked by microscope on side face of the specimens of 2.25Cr1MoV, after fatigue tests were completed, shown in Fig. 6. The fatigue cracks propagate mainly transgranularly at room temperature, while they propagate mainly intergranularly at high temperature. There are some secondary cracks taking place during main crack propagation at high temperature. The fatigue cracks at intermediate temperature are combination of transgranular and intergranular cracks.



(a) Transgranular fatigue crack at room temperature

(b) Transgranular fatigue crack at 350℃



(c) Intergranular fatigue crack with secondary cracks at 500℃

Fig.6 Crack propagation shape on side face of the specimens of 2.25Cr1MoV

Oxidation, creep, decrease of strength and Young's modulus can result in change of fatigue crack growth at high temperature. This test temperature is not over 500℃, so there is hardly creep in the tests. The strength and Young's modulus decrease with increase of test temperature, and result in increase of fatigue crack growth.

Oxidation at high temperature affects fatigue crack propagation in the following two aspects:① Oxidation on the crack surfaces can result in fatigue crack closure, and effective stress intensity factor decreases, so crack growth rate also decreases. When thickness of oxidation layer occupies the main parts of the crack opening displacement with lower ΔK, fatigue crack closure is obvious. This is why the da/dN at 200℃is slightly lower than that at room temperature under low ΔK condition. ② Oxygen can easily spread intergranularly at crack tip and combine with Cr, Fe into oxide, so intergranular resistance to fatigue decreases and fatigue crack propagates intergranularly. Fatigue crack growth rate increases. Therefore fatigue crack propagation is affected by both crack surface oxidation and intergranular oxidation.

CONCLUSIONS

A series of fatigue crack growth tests were carried out, and fatigue crack growth rates were obtained at 25~500℃ for 16MnR, 2.25Cr1Mo and 2.25Cr1MoV steels.

The fatigue cracks of 16MnR propagate more slowly at 150℃ and 300℃ than at room temperature and 425℃.

The crack growth rates increase with the temperature at temperature over 200℃ under test ΔK condition for 2.25Cr1Mo and 2.25Cr1MoV steels. The fatigue crack growth rates at room temperature and 200℃ have little difference. The fatigue crack growth rates at the same temperature for 2.25Cr1Mo and 2.25Cr1MoV are nearly the same.

The fatigue cracks propagate mainly transgranularly at room temperature, while they propagate mainly intergranularly at high temperature.

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