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CREEP AND CREEP-FATIGUE CRACK GROWTH BEHAVIORS OF 30Cr1Mo1V ROTOR STEEL AFTER LONG TERM SERVICE

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ABSTRACT

This paper presents the creep and creep-fatigue crack growth behaviors of 30Cr1Mo1V turbine rotor steel which had been in service for 16 years. Two typical sections of the rotor, i.e. high and low temperature sections, are examined at 538℃, with crack initiation and propagation monitored by D.C. potential drop method in a compact tension (CT) specimen. The material of the high temperature section has the lower resistance to creep and creep-fatigue crack growths than the low temperature section. The creep crack initiation (CCI) time decreases with the increase of initial stress intensity factor. The creep-fatigue crack growth (CFCG) is dominated by the cycle-dependent fatigue process when the hold time at the maximum load is shorter, but it becomes dominated by the time-dependent creep process when the hold time becomes longer. The high temperature section shows a larger influence of time-dependent creep behavior on CFCG than the low temperature section.

1. INTRODUCTION

The turbine rotors in power plants are often subjected to variable loading conditions during service such as creep, fatigue and creep-fatigue, which leads to the initiation of cracks from the pre-existing defects in manufacturing or the damages in deformation. The creep arises from the high pressure on the rotor at high temperature, and the fatigue is due to the alternating thermal stresses developed during turbine start and stop. Such multiple loading conditions can induce the appearance of a macro-crack evolved from some inherent micro-defects or deformation damages such as inclusions and voids. The crack initiation, from the viewpoint of fracture mechanics, does not mean the failure of component since the unstable crack propagation happens only when the initiated crack grows to a certain size. There is generally a long period of time for the crack to initiate and grow to the critical size under creep-fatigue loading condition. To ensure the safety and reliability of operation, it is necessary to study the creep-fatigue lifetime of turbine rotor in service conditions.

Cr-Mo-V steel is the typical material for turbine rotors in supercritical power plants. Many experimental and theoretical studies have been made to predict the service lifetime, focusing on the effects of stress level, hold time and temperature on the creep-fatigue crack initiation and growth [1-2]. However, most of them are based on the as-received material, and fewer are reported for the performance of Cr-Mo-V steel which has been in service for a long time. Studying the changes of the creep-fatigue crack growth behaviors of rotor steel after long-term service is helpful to not only the better understanding of the effect of service conditions on the material property, but also the reliable analysis of material degradation and life expenditure that serve basis for the management and assessment of rotor lifetime.

In this paper, an experimental investigation on the crack growth behavior of 30Cr1Mo1V (1Cr-1Mo-0.25V) rotor steel that has been operated for 16 years is carried out in both creep and creep-fatigue conditions. Tests are performed in the compact tension (CT) specimens at 538℃ for two typical sections of the rotor, i.e. high and low temperature sections. The effects of initial stress level and hold time on the crack initiation and propagation are studied via D.C. potential drop method.

2. EXPERIMENTAL PROCEDURES

2.1 Materials and specimens

The material used is 30Cr1Mo1V turbine HP-IP rotor steel, which had been in service for 16 years in subcritical plant. The chemical composition of the steel is shown in Tab.1. Two typical sections of the rotor, i.e. high and low temperature sections, are investigated as shown in Fig.1. The mechanical properties of materials at these two sections are shown in Tab.2. The property of high temperature section has degraded after long-term service, but the low temperature section still satisfies the performance requirement of ASTM A470-03[3]. The service temperature and stress calculated by finite element analysis according to the rotor's service condition are shown in Tab.3. The high temperature section worked at a temperature more than 500℃ and the other at the room temperature, but the stresses in both of the sections are very small.

The specimen used is a standardized CT specimen for creep crack growth tests based on ASTM E1457-00[4]. The height, width and thickness are 24, 25, and 10mm, respectively. All specimens were notched by Electrical Discharge Machining (EDM).

Tab.1 Chemical composition of 30Cr1Mo1V steel (wt.%)

C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Al
0.29	0.22	0.75	0.007	0.002	0.43	1.12	0.06	1.20	0.27	≤0.005

Tab.2 Mechanical properties of examined materials

Sampling location	$R_{P0.2}$/MPa	R_m/MPa	A/%	Z/%
High temperature section	608	761	19.0	60.3
Low temperature section	640	810	19.1	54.2
Original material	630	790	22.4	65.2
ASTM A470-03	≥620	725-860	≥17	≥43

Tab.3 Service temperature and stress of specimen

Section	Low temperature section	high temperature section
Temperature(℃)	25	525
Von Mises Stress (MPa)	67.4	22.6

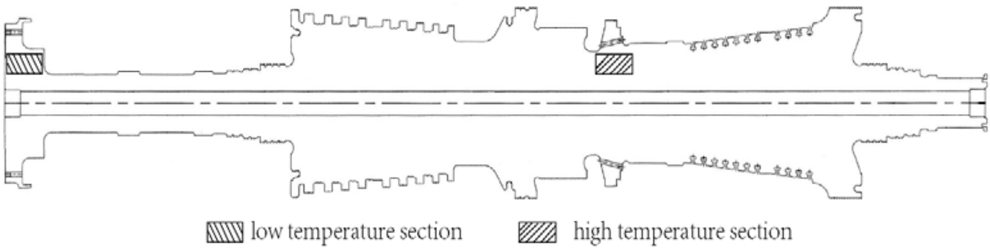

Fig.1 Sketch map of steam turbine rotor

2.2 Test method and conditions

The creep crack growth (CCG) tests are conducted based on ASTM E1457-00. The test temperature is kept at 538℃ with the precision of ±1℃. Dead weight loading is applied with initial stress intensity factor K_I in the range of 25 to 45 MPa·m$^{1/2}$. The load waveform of the creep-fatigue tests is shown in Fig.2. A stress ratio of 0.1 is kept constant, but the hold time (t_h) at the maximum load varies from 1 to 120 minutes in different tests. The crack length is measured by DCPD method.

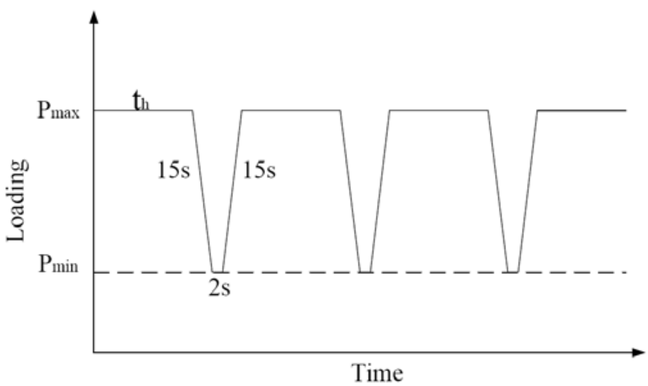

Fig.2 Load waveform adopted in creep-fatigue tests

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1Creep crack growth behavior

Similar to the creep curve, the creep crack growth (CCG) curve of both high and low temperature sections can be divided into 3 stages, as shown in Fig.3. The crack growth first experiences a relative long stage with the slow increasing rate, and then reaches essentially a steady stage in which the rate changes little with time, and finally the crack rapidly grows with time until fracture occurs. The first stage can be considered as the incubation of creep crack. It generally defines the time for the crack to grow to a size of 0.2 mm as the crack initiation time [5]. As shown in Fig.4, the creep crack initiation (CCI) time decreases with the increase of initial stress intensity factor, yet following an approximately linear logarithmic relation. In addition, the CCI time of high temperature section is smaller than that of the low temperature section, which is an indication of material degradation of resistance to crack growth at the high temperature section.

Fig.5 shows the CCG rate da/dt as a function of stress intensity factor K. The curve of each condition is a typical CCG rate curve [6]. The CCG rate increases with the increase of K at the first stage, then comes to a flat stage in which the rate change little with K, and finally it grows rapidly with the stress intensity factor. Again, material at the high temperature section has a degraded resistance to creep crack growth, because the CCG rate of the high temperature section was much higher than that of the low temperature section under the same loading.

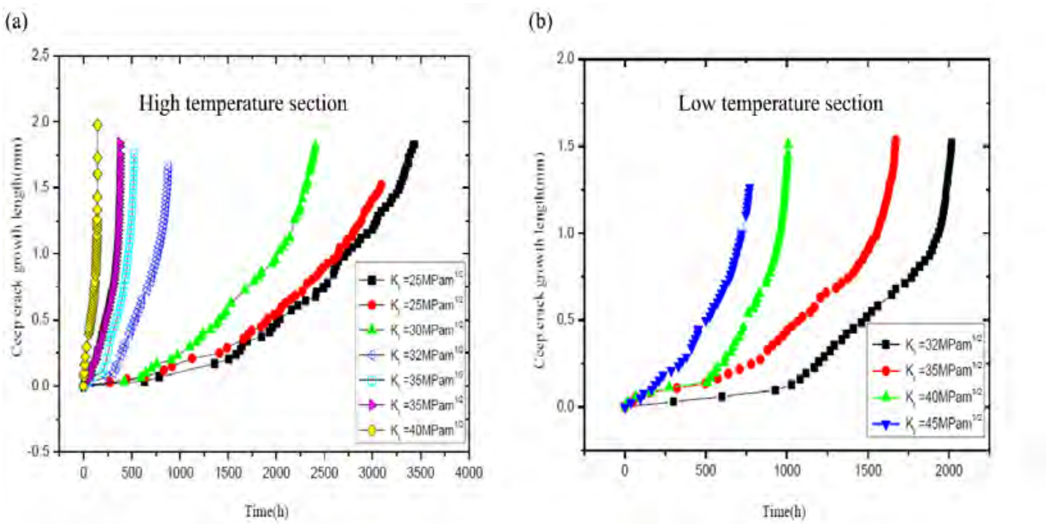

Fig.3 Creep crack growth length versus time for different initial stress intensity factor K_I of (a) the high temperature section and (b) the low temperature section.

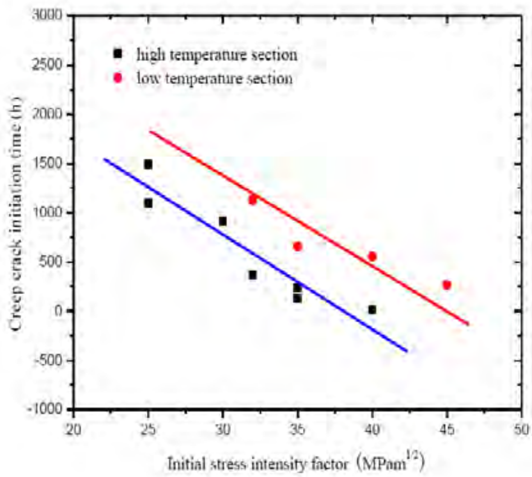

Fig.4 Creep crack initiation time t_0 versus initial stress intensity factor K_I

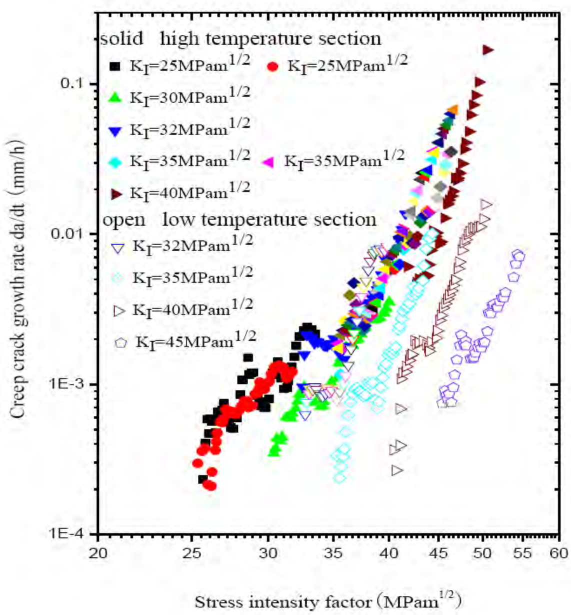

Fig.5 Creep crack growth rate da/dt versus stress intensity factor K

3.2Creep-fatigue crack growth behavior

Different from the CCG curves, the creep-fatigue crack growth (CFCG) curves have marginal incubation stages, especially when the hold time becomes short, as shown in Fig.6. The introduction of fatigue condition effectively reduces the creep-fatigue crack initiation (CFCI) time, which is found to decrease with the reduction of hold time at the maximum load. When the hold time is reduced to 1 min, no visible incubation period can be observed from the CFCG curves for both high and low temperature sections. Similar to the situation in pure creep condition, the high temperature section has the lower resistance to CFCG than the low temperature section.

The CFCG rate can be defined as crack growth length per time (da/dt) or crack growth length per cycle (da/dN). They are often used together to differentiate the effects of creep and fatigue on the crack growth, as to be discussed below. The relations of da/dt and da/dN with the stress intensity factor range ΔK are shown respectively in Figs.7a-b for the high temperature section, and respectively in Figs. 8a-b for the low temperature section. The CFCG rate da/dt is generally larger than the CCG rate, but the difference in between decrease with the increase of hold time (Fig. 7a and 8a). . As for the rate da/dN, it shows weak dependence on the hold time when the hold time itself is shorter (e.g. 1-10 min in Figs. 7b and 8b). Only when the hold time becomes longer (e.g. >30 min) da/dN increases with the increase of hold time..

To examine the influences of creep and fatigue on the crack growth behavior, a relationship between the CFCG rate at a given stress intensity factor of $\Delta K=36MPam^{1/2}$ and the frequency is constructed, as shown in Fig.9. The frequencies are transferred from the hold times. The CFCG rate da/dt depends greatly on the frequency when the frequency itself is higher, so the crack growth behavior in this case is dominated by the cycle-dependent fatigue process. With the decrease of frequency, i.e. the increase of hold time, the dependence becomes weaker due to the contribution of the time-dependent creep process. Similar effects were reported by O Yokota et al. [7] for the creep-fatigue crack growth of 12Cr steel.

The influence of time-dependent creep behavior on CFCG at the high temperature section is larger than that at the low temperature section. This is supported by the facts that the slope of da/dt-f curve of the high temperature section is smaller than the low temperature section (Fig. 9a), and the scope of hold time in which the CFCG rate da/dN changes little is narrower in the former than in the latter (Fig.9b). The reason could be that the creep property of the high temperature section has degraded after long term service compared to the low temperature section.

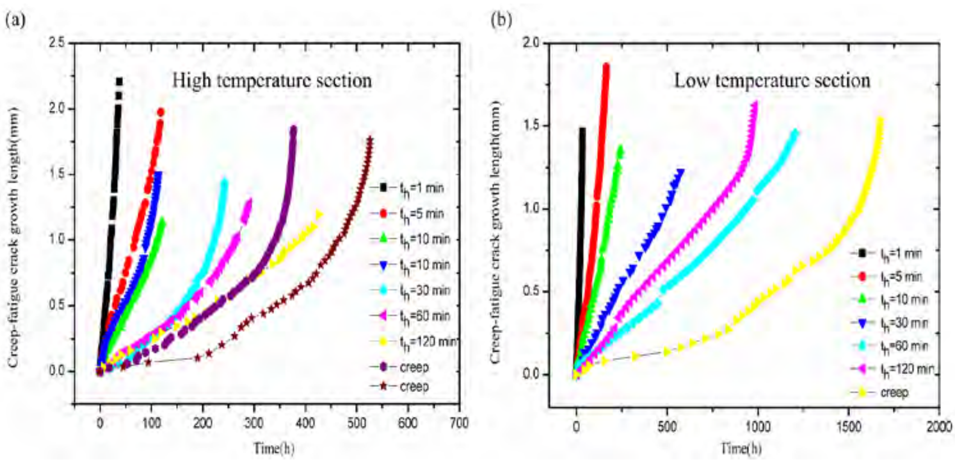

Fig.6 Creep-fatigue crack growth rates of (a) da/dt and (b) da/dN versus stress intensity factor range ΔK of the high temperature section.

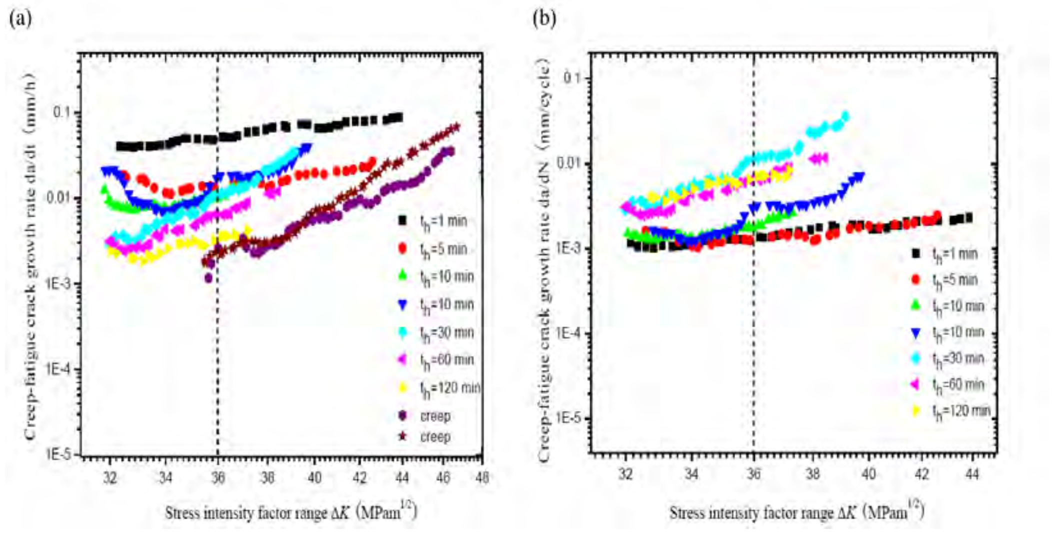

Fig.7 Creep-fatigue crack growth rates of (a) da/dt and (b) da/dN versus stress intensity factor range ΔK of the high temperature section.

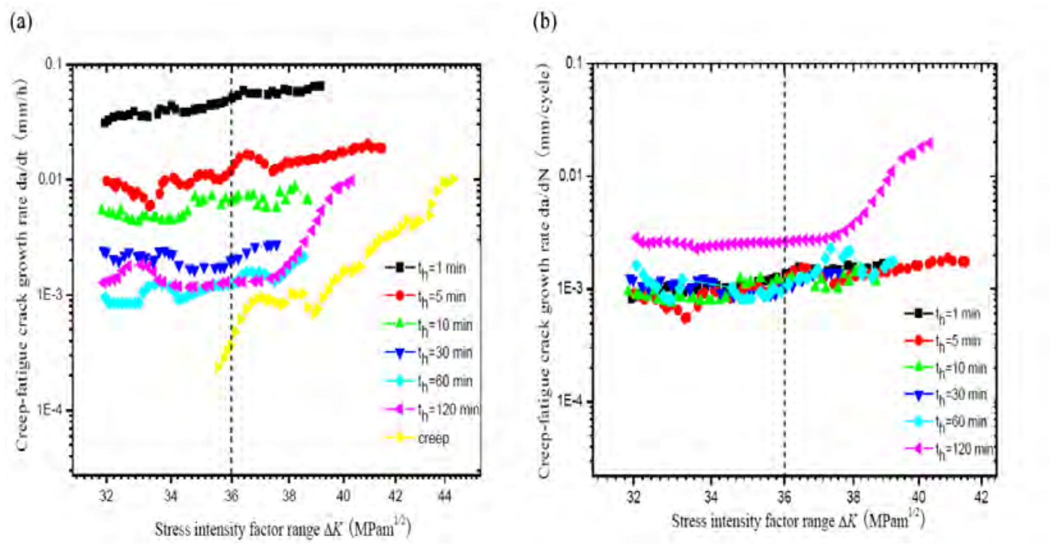

Fig.8 Creep-fatigue crack growth rates of (a) da/dt and (b) da/dN versus stress intensity factor range ΔK of the low temperature section

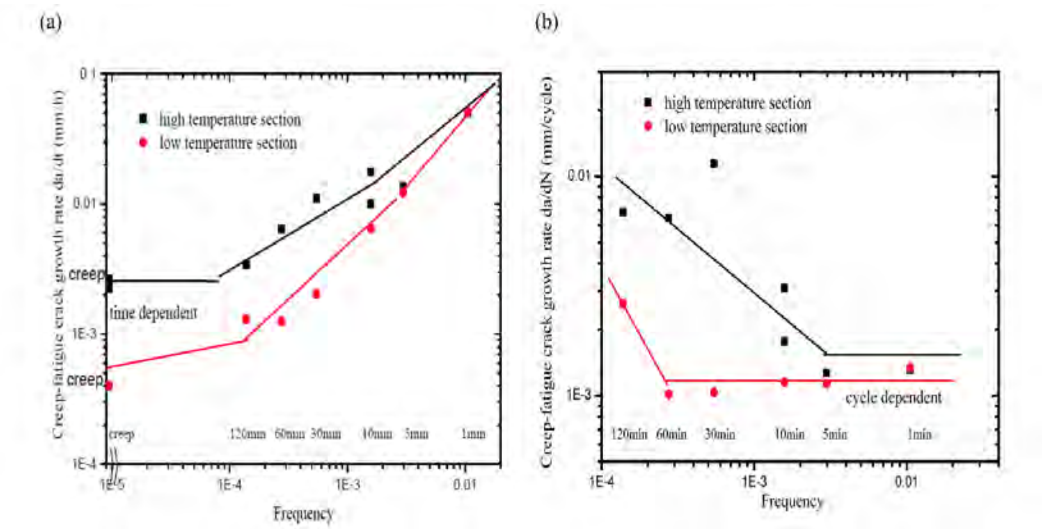

Fig.9 Creep-fatigue crack growth rate of (a) da/dt and (b) da/dN with range of stress intensity factor ΔK

4. CONCLUSIONS

An investigation has been carried out on the creep and creep-fatigue crack growth behaviors of 30Cr1Mo1V steel which had been operated for 16 years. The following conclusions can be drawn from the current investigation:

(1)The material resistance to creep and creep-fatigue crack growth of the high temperature section has decreased, comparing to the low temperature section.

(2) Introduction of fatigue condition promotes the crack initiation and growth. The creep-fatigue crack growth behavior is dominated by the cycle-dependent fatigue process when the hold time is shorter, but it turns to be dominated by the time-dependent creep process when the hold time is longer.

(3) The time-dependent creep behavior affects the CFCG at the high temperature section more greatly than at the low temperature section.

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