CRACK GROWTH CHARACTERISTICS UNDER HIGH TEMPERATURE FATIGUE-CREEP MULTIPLICATION CONDITION

Mitsuo Yoda [1], Osamu Yokota [1]
Masayuki Kanou [2] , Toshimitsu Yokobori [3]

[1] Department of Mechanical Engineering, College of Engineering, Nihon University, Tamuramachi, Koriyama, Japan
[2] Graduate School, College of Engineering, Nihon University, [2]Tamuramachi, Koriyama,Japan
[3] Department of Mechatronics and Precision Engineering, Tohoku University, Aoba, Aramaki, Aobaku, Sendai Japan

Abstract

12 Cr heat-resisting steels have been developed for the high efficiency heat resisting steels of boiler and turbine and high temperature plant materials. These materials have been used under fatigue, creep and fatigue-creep multiplication conditions under corrosive environment and elevated temperature. It is necessary to clarify the effects of stress holding time, stress rising time, stress decreasing time, stress frequency on time-dependent fracture or crack growth under creep and fatigue-creep conditions at high temperatures. However, there are few papers in which each factor was systematically obtained.

In this paper, creep test and fatigue-creep multiplication condition test were conducted using compact tension (CT) specimens of HT1200 steel at high temperatures of 600 °C, 650 °C and 700 °C. In order to clarify strength mechanism of this material, both load line displacement and crack growth length were measured. Micro-structural and macro-structural fracture surfaces were also observed by optical microphotography and scanning electron microscope and so on.

Key words

Fracture, Crack growth rate, Load line displacement, High temperature, Fatigue-creep multiplication condition , Stress intensity factor, Scanning electron microscope, Activation energy.

1. Introduction

Many components in high temperature applications are subjected to variable loading patterns during service such as creep, fatigue and creep-fatigue. Creep-fatigue behavior is a complex problem of cyclically applied loading at high temperatures where time-dependent, thermally activated process can occur. The crack growth rate under the conditions of the creep-fatigue interaction will reflect the creep process and the fatigue process dominant near the crack tip. The majority of early work on high temperature structural alloys was concerned with static creep or fatigue testing. The crack growth rates in these cases were correlated with the parameters [1-3] such as the stress intensity factor, C^* integral, crack opening displacement and Q^* parameter.

Recently, the combined effects of temperature and frequency on the crack growth rate under creep-fatigue interaction have been determined and analyzed on the basis of the Arrhenius thermally activated process [4,5]. It has been shown that the activation energy thus obtained decreases with decreasing hold-time. The stress wave shapes such as triangular form and trapezoidal form have a strong effect on the crack growth rate. Similar effects of temperature and frequency were observed in terms of the failure life .

In this paper, the creep-fatigue tests were performed on the compact tension type specimens of 12 Cr steel at various combinations of temperatures and frequencies. The combined effects of temperature and frequency on the crack growth and the failure life were determined and analyzed based on the thermally activated processes.

2. Specimens and Experimental Procedure

The material used was 12 Cr steel (HR1200), and its chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The test specimens were of compact tension (CT) type with side grooves, as shown in Fig.1. The width W and the thickness B of the specimen were 50.8 and 25.4 mm, respectively. All the tests were performed using the lever-arm high temperature creep-fatigue machine, which could apply stress cycles involving various hold-times to the specimens. The amount of crack growth was measured using the electrical potential method and calculated by Johnson's formula. The stress wave form used for the creep-fatigue loading is shown in Fig.2. The gross stress σ_g and the frequency f are given as

$$\sigma_g = \frac{P}{B_1(W-a)}\left\{1+\frac{3(W+a)}{W-a}\right\} \qquad (1)$$

$$f = \frac{1}{(2t_R + t_H)} \qquad (2)$$

Table.1 Chemical composition (%)

	C	Si	Mn	Ni	Cr
12Cr-2.51W (HR1200)	0.10	0.06	0.46	0.25	10.21

Mo	W	V	Nb	Co	N	B
0.14	2.51	0.21	0.07	2.44	0.017	0.013

Table.2 Mechanical properties

	Temperature (°C)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
12Cr-2.51W (HR1200)	20	705	853	19.3
	650	294	386	31.7

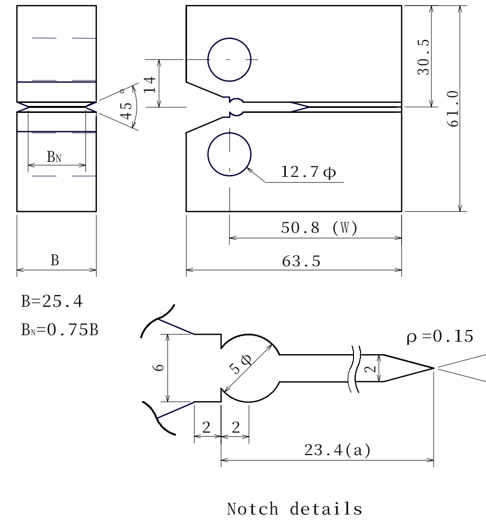
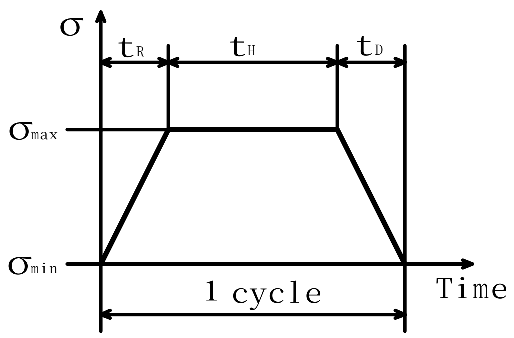


Figure 1 CT specimen geometry and size



t_R : Rising time (30s)

t_H : Hold time

t_D : Descending time(30s)

Figure 2 Stress wave form

where t_H is the hold-time, t_R the time for rising or descending stress rate. The tests were performed using four different hold-times t_H of 2, 10, 60 and 600s., resulting in frequencies of 1.6 x 10^{-2}, 1.4 x 10^{-2}, 8.3 x 10^{-3} and 1.5 x 10^{-3} Hz, respectively. The test temperatures were 600, 650 and 700°C and the temperature variation was ± 2 °C. The specimens were preheated, subjected to 10 % of the test load to maintain the alignment, at the test temperature for 16 hours and then loaded to a given stress cycle. The creep tests ($t_H = \infty$) were also performed under the constant stress at each temperature.

3. Experimental Results and Discussion

Figures 3 and 4 show the load line displacement $\Delta\delta$ and the crack growth Δa versus the time t normalized to the failure time t_f, respectively, at temperature 650°C. The load line displacement grows gradually until it is accelerated around $t / t_f = 0.8$. The $\Delta\delta - t / t_f$ curves fall on the same line independent of the hold times. However, the $\Delta a - t / t_f$ curves depend on the hold time. There is the region of nearly constant crack growth rate that occupied more than 60 % of the failure time t_f, as shown in Fig.4. The crack growth rate da/dt is plotted as a function of the load line displacement rate at

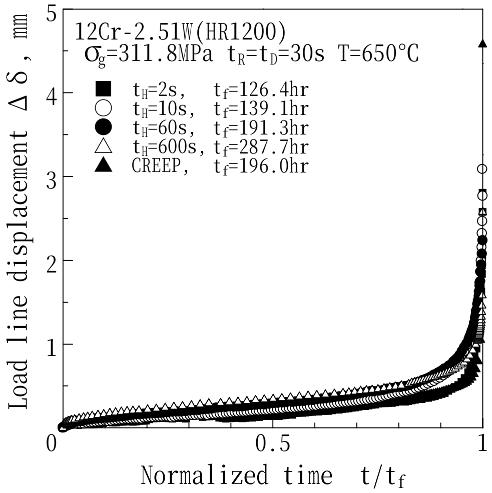


Figure 3 Load line displacement $\Delta\delta$ versus normalized time t/t_f (650 °C)

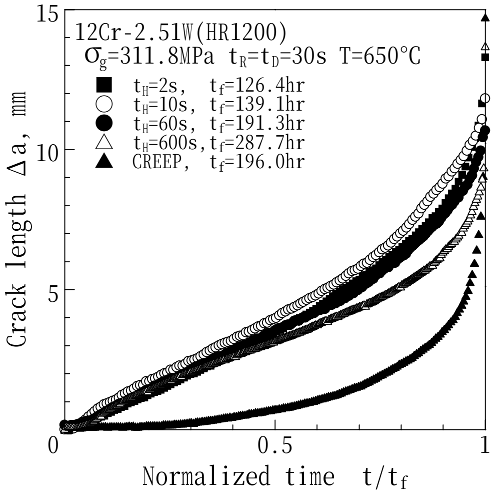


Figure 4 Crack growth Δa versus time t/t_f (650 °C)

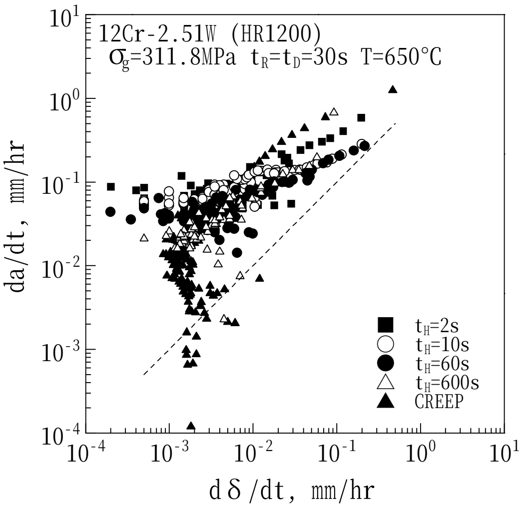


Figure 5 Crack growth rate da/dt versus load line displacement rate $d\delta/dt$ (650 °C)

temperature 650 °C in Fig.5. For creep ($t_H = \infty$) and t_H = 600 s, the da/dt – dδ/dt curves initially have a typical trend of nose-like shape and then da/dt is proportional to dδ/dt. For hold-times less than t_H = 60s, dδ/dt is accelerated more than da/dt over the entire range of the experiment.

The crack growth rate da/dt is plotted as a function of the stress intensity factor range ΔK for temperatures 650 and 700°C, in Figs.6 and 7, respectively. The stress intensity factor is given as follows.

$$K = \frac{P}{B_1\sqrt{W}} f(a/W) \tag{3}$$

where

$$f(a/W) = \frac{(2 + a/W)}{(1 - a/W)^{3/2}}\{0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.60(a/W)^4\}$$

It is evident that the crack growth rates, measured at each combination of temperature and frequency are largely different. As described above, there are two regions, region I for the constant crack growth rate expect for creep and region II for the accelerating crack growth rate. The constant or steady-state crack growth rate occupies more than 60 % of the failure life. Figure 8 shows the side view of fracture surface at the middle of the specimen thickness for t_H=2s. Crack branching deviating from the main crack can be observed to occur at many sites under the creep-fatigue condition, while there exists no crack branching under the creep condition. The constant crack growth rate may be attributed to crack branching.

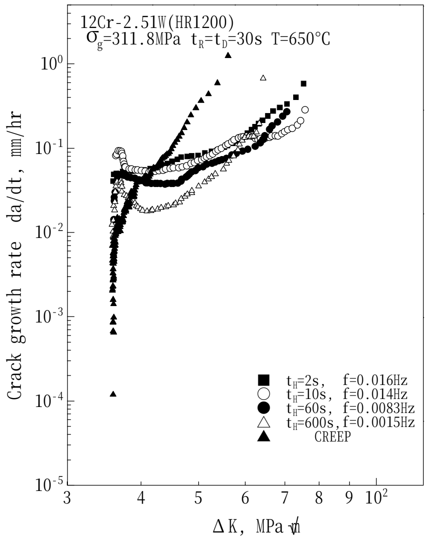


Figure 6 Crack growth rate da/dt versus stress intensity factor range ΔK(650 °C)

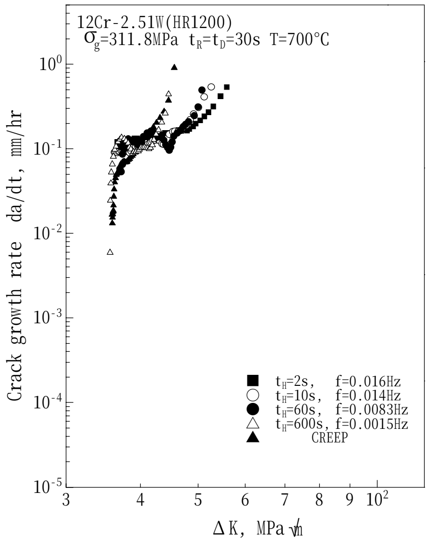


Figure 7 Crack growth rate da/dt versus stress intensity factor range ΔK(700 °C)

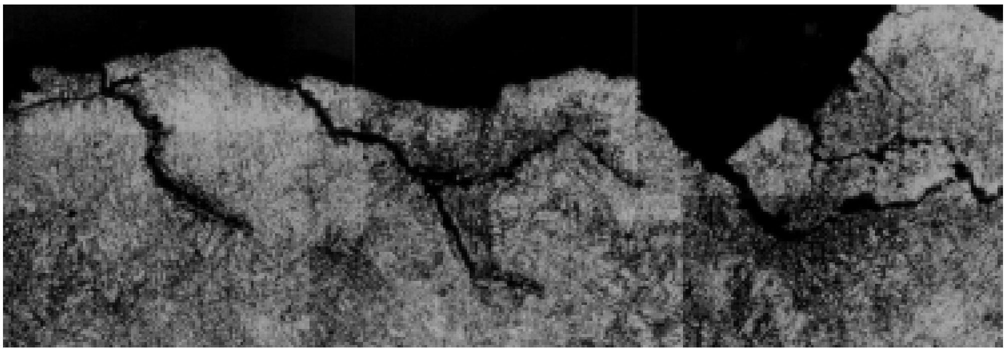


Figure 8 Side view of fracture surface at 650 °C

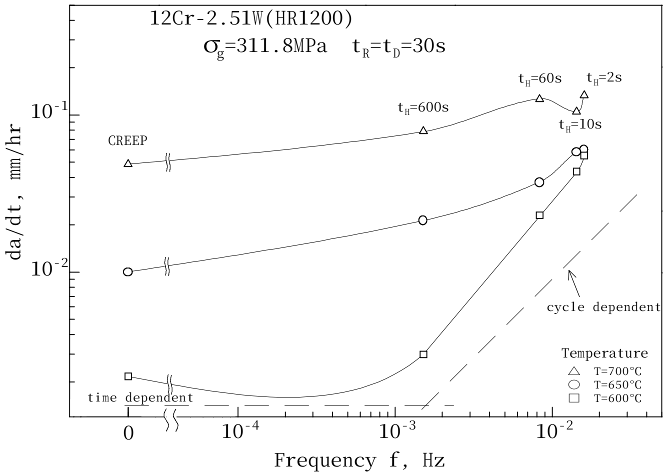


Figure 9 Dependence of constant crack growth rate da/dt on frequency f for various temperatures

The combined effects of temperature and frequency on the constant crack growth rate are shown in Fig.9. The dependence of the crack growth rate on frequency can be explained in terms of the following relationship between the crack growth per cycle da/dN and the crack growth rate da/dt

$$da / dt = fda / dN \tag{4}$$

At high frequencies where da/dt is proportional to frequency, the crack growth per cycle is insensitive to frequency and cycle-dependent fatigue process is dominant. The da/dt decreases gradually with the decreasing frequency and the trend towards a horizontal line in Fig.9 at low frequencies corresponds with where da/dt is constant and time-dependent creep mechanisms will be expected to dominate. As the temperature increases, the difference of the crack growth rates between creep, fatigue and creep-fatigue interaction is small. Dependence of the constant crack growth rate on temperature can be explained on the basis of the thermally activated process, in terms of the relationship between da/dt and the reciprocal of absolute temperature T, as shown in Fig.10. The constant crack growth rate can be expressed as [5].

$$da / dt = AK_{in}^{n} \exp\left(-Q / RT\right) \tag{5}$$

where A and n are the constants, K_{in} the initial stress intensity factor, Q the activation energy for the crack growth of the creep, and creep-fatigue interaction conditions, R the gas constant and T the absolute temperature. In this experiment, K_{in} is constant and the activation energy Q for each hold-time

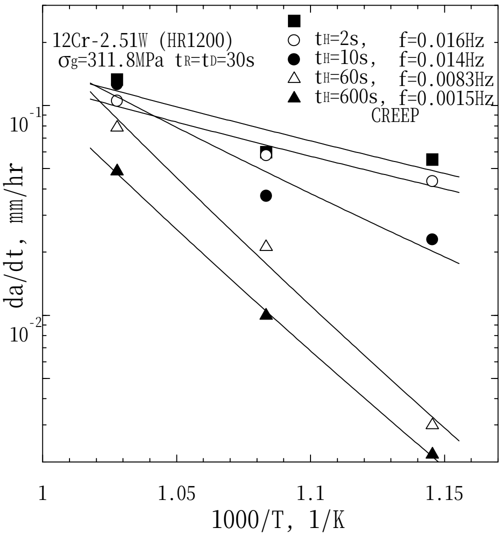


Figure 10 Dependence of constant crack growth rate da/dt on temperatures T

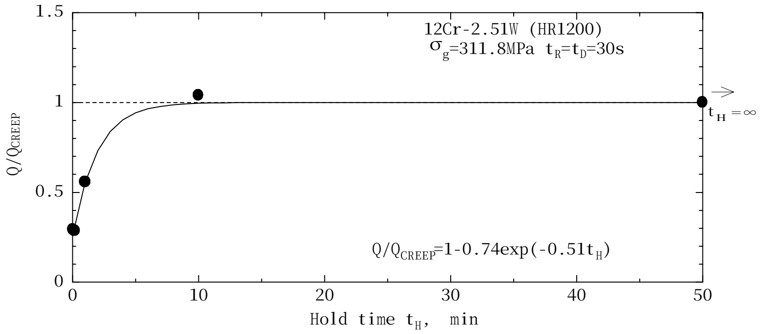


Figure 11 Variation of normalized activation energy Q/Q_{CREEP} with hold-time t_H

can be calculated from the slope of the curve. Although the activated energy tends to decrease as the temperature decreases for higher frequencies, the average value of Q over the range of the test temperatures can be obtained from the slope of the da/dt – l/T curve for each frequency. The value of Q normalized to the value of Q_{CREEP} for the creep crack growth is plotted as a function of the hold-time t_H in min, as shown in Fig.11. The normalized activation energy Q/Q_{CREEP} decreases with decreasing hold-time and the activation energy Q can be expressed as

$$Q = Q_{CREEP} \left[1 - A'\exp\left(- B't_H\right)\right] \qquad (6)$$

where, A' and B' are the constants. The value of Q_{CREEP} is 220.3 kJ/mol, the constants A' and B' are 0.74 and 0.51, respectively. The dependence of the constant crack growth rate on temperature can be described based on the thermally activated processes by taking account of the hold-time under the creep- fatigue interaction condition.

4. Conclusions

The creep, fatigue and creep-fatigue interaction tests were performed on the compact tension specimens of 12 Cr steel at three different temperatures. The crack growth rates were correlated by the stress intensity factor and there is the region of the constant crack growth rate that occupies more than 60 % of the failure life. At high frequencies where the constant crack growth is proportional to the frequency, cycle-dependent fatigue processes are dominant. The trend towards the horizontal line at low frequencies corresponds to the creep processes where the crack growth rate is independent of frequency. Dependence of the constant crack growth rate on temperature can be described on the basis of the thermally activated processes by taking account of hold-time.

References

1 J.D.Landes and J.A.Begley, 1976,ASTM STP590,pp128-148.

2 K.M.Nikbin, D.J.Smith and G.A.Webster, 1986, The Journal of Engineering Materials and Technology, Trans. ASTM'108, pp.186-191.

3 A.T.Yokobori, H.Tomizawa, H.Sakata, T.Kako and T.Kuriyama, 1987, Engineering Fracture Mechanics, 28, No.56, pp. 805-816.

4 A.T.Yokobori, H.Sakata, and T.Yokobori, 1980, Tans. Japan Soc. Mech. Engrs. 46, No.410, pp. 1062-1071.

5 A.T.Yokobori,Jr., T.Uesugi, T.Yokobori, A.Fuji, M.Kitagawa, I.Yamaya, M.Tabuchi and K.Yagi,1998, Journal of Materials Science 33, pp1555-1562.