ESTIMATION OF CREEP CRACK GROWTH RATE FROM CIRCULAR NOTCHED SPECIMEN

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ABSTRACT

A circular notched specimen was used to investigate the creep crack growth rate under multi-axial stress condition. A circular notch in a round bar specimen produces multi-axial stress field when uni-axial stress is applied in the axial direction. An electric potential drop method is adopted to measure crack length. In this paper, an equation for the relationship between the electric potential drop and the crack length of circular notch in a round bar is proposed and the accuracy of the measured length of a crack using this method was compared with the actual crack length. Using this equation, high temperature creep crack growth tests were conducted for a circular notched specimen of CrMoV steel.

KEYWORDS

Circular notch, multi-axial stress, electric potential drop method, creep crack growth, creep fracture life, thermal activated process

INTRODUCTION

The characteristics of crack growth rate under multi-axial stress condition have been investigated by many researchers using several methods[1-3]. Under the uni-axial tensile stress condition, a round bar specimen with a circular notch produces crack growth data under multi-axial stress condition[4]. We used a circular notched specimen to investigate the creep crack growth rate under multi-axial stress condition. An electric potential drop method was adopted to measure the crack length. The electric potential drop method bases on the fact that the potential distribution in the vicinity of a crack changes with crack growth[5]. A calibration curve is necessary to convert the value of electric potential drop into crack length. An equation which relates crack length to the electric potential has been obtained for CT specimen[5,6]. The equation can be applied to the measurement of a crack length for the center-cracked specimen, a single-edge notched specimen, a CT specimen and others, but it cannot be applied to the circular notched specimen. Therefore, the derivation of a relationship between the value of electric potential drop and the crack length for circular notch for a round bar specimen was conducted. The accuracy of the measured length based on this method was compared with the actual crack length[7].

High temperature creep crack growth tests were conducted for a circular notched specimen of CrMoV steel. The crack length was measured using the proposed equation in this paper and the law of creep crack growth rate was derived on the basis of a thermal activation process.

MATERIAL AND SPECIMEN

Material used is a CrMoV steel. The chemical composition and mechanical properties at room temperature are shown in Tables 1 and 2, respectively. The material is used for a turbine rotor (400mm in diameter) and made by Japan Steel Works, Ltd.

TABLE 1 Chemical composition of CrMoV steel

(Wt%)

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.3	0.22	0.74	0.005	0.0016	0.36	1.1	1.32	0.23

TABLE 2 Mechanical properties of CrMoV steel

0. 2% Y. S. Mpa	T. S. Mpa	EL. %	R. A. %
682	830	23.8	62.4

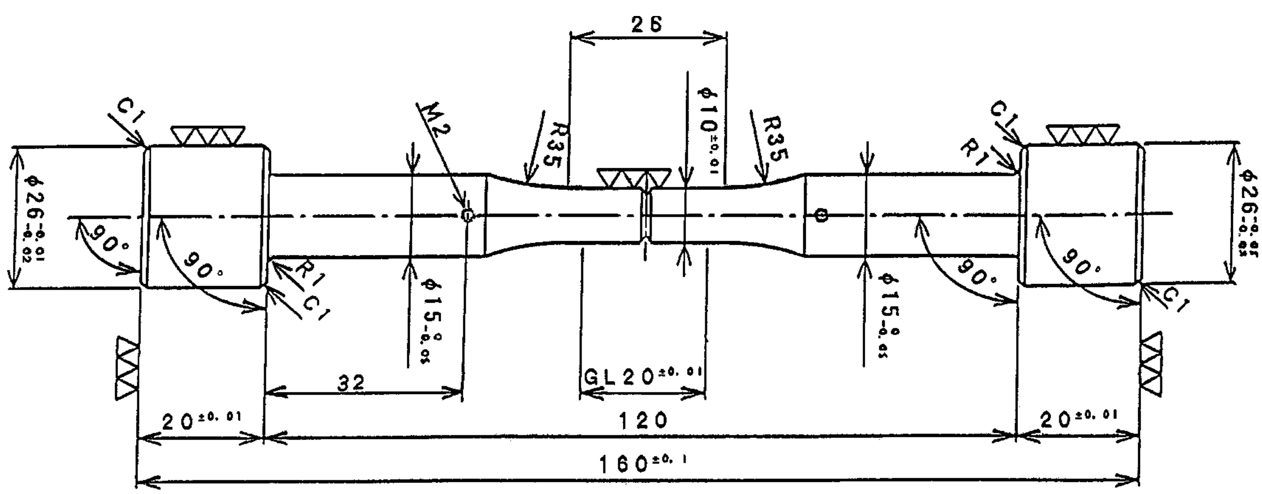


Fig. 1: Dimension of a circular notched specimen used in the creep test.

The geometry and dimension of a specimen is shown in Fig. 1. The circular notch is machined and notch tip angle, ϕ is 60º, notch depth, a_0 is 1.5mm and notch root radius, ρ is 0.25mm. The stress concentration factor is 3.85[8]. The stress intensity factor is given by Eqn.(1)[9],

$$K=\frac{1}{2}\sigma_{net}\left(\pi ad/D\right)^{1/2}\left(1+\frac{1}{2}\lambda+\frac{3}{8}\lambda^{2}-0.363\lambda^{3}+0.731\lambda^{4}\right)\left\{1+0.1\left(\frac{a}{D}\right)^{1/2}\left(1-\frac{2a}{D}\right)\right\}, \qquad (1)$$

where σ_{net} is net stress, D is diameter of specimen, $d=D-2a$ (a is crack length which include notch depth), as shown in Fig. 3 and $\lambda=d/D$.

TEST METHOD

According to the electric potential drop method, an electric current is applied to the specimen and the value of electric potential drop is measured. The crack length of CT, CTT, SENT and SENB specimen can be evaluated by Johnson's equation[5,6] as given by;

$$a = \frac{2W}{\pi}\cos^{-1}\frac{\cosh(\pi y/2W)}{\cosh\left\{(U/U_0)\cosh^{-1}\left[\cosh(\pi y/2W)/\cos(\pi a_0/2W)\right]\right\}} \tag{2}$$

where U_0 and a_0 are the initial values of potential and crack length, respectively. U and a are the actual values of potential and crack length, and y is one half of the gage span for U and W are shown in Fig. 2. For circular notched specimen, Eqn. (2) may not be applied. Thus, a calibration curve which converts the value of electric potential drop into the crack length is necessary to measure crack length initiated from a circular notch. The calibration curve which adjust to a circular notch was recently formulized by modifying Johnson's equation as follows[7]:

$$a = 0.973\exp\left[0.289\frac{D}{\pi}\cos^{-1}\frac{\cosh(\pi y/D)}{\cosh\left\{(U/U_0)\cosh^{-1}\left[\cosh(\pi y/D)/\cos(\pi a_0/D)\right]\right\}}\right] \tag{3}$$

where D is diameter of specimen, as shown in Fig. 3. The deviation of the measured crack length by Eqn. (3) from the actual crack length is 4% until crack length, $2a/D$ becomes 0.75[7].

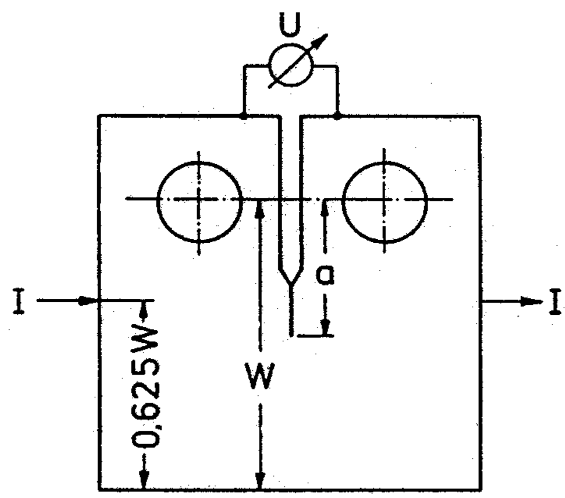


Fig. 2: Dimension of CT specimen.

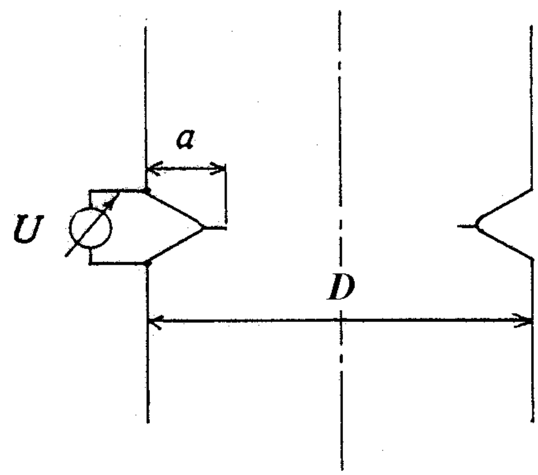
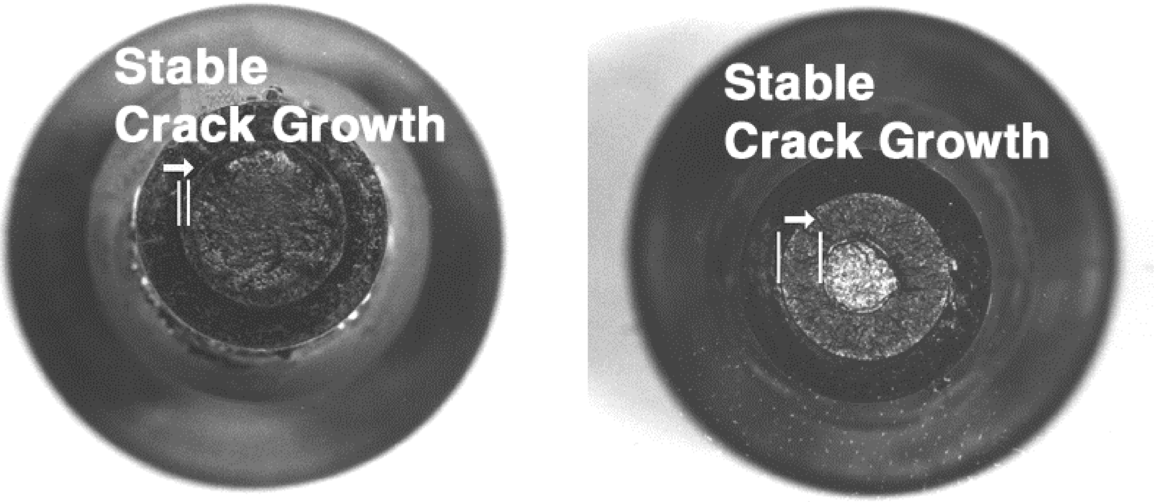


Fig. 3: Virtual Section of circular notched specimen.

To measure crack length by electric potential method, electrodes are connected to a specimen. Potential leads made of stainless steel wire (0.5mm in dia.) are welded on specimen in the vicinity of notch, as shown in Fig. 3. Current leads (2mm in dia.) made of stainless steel wire are attached to the shoulder part of specimen. The potential measurement and current input are located on a same centerline. The specimen with electrodes is heated up to test temperature. Creep tests are conducted at 538°C, 566°C and 594°C. Three applied loads, 13328N, 17640N and 21972N, are selected. The crack length is measured continuously during the creep crack growth test.

RESULTS AND DISCUSSION

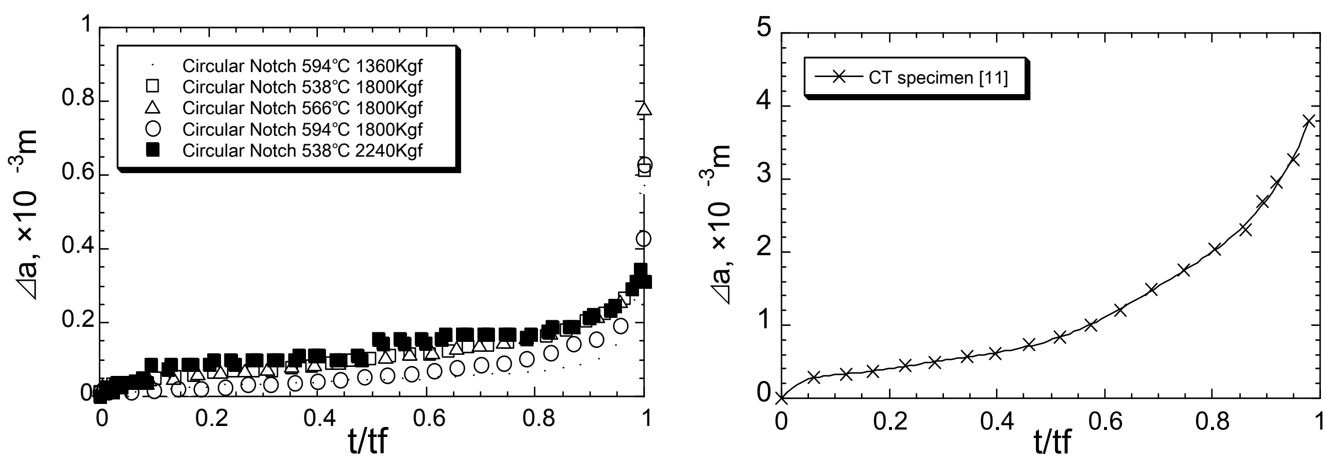
The crack extension behaviour of a circular notch was in Fig.4. The crack front shows a circle of which center was almost identical with the center of the original round bar specimen with a circular notch, as shown in Fig. 4. From this result, the definition of a crack length in this paper is reasonable.



(a) The fracture surface tested under creep condition (17640N, 538°C). (b) The fracture sureface tested under strain controlled fatigue condition ($\Delta\varepsilon$ =0.4%, 594°C).

Fig. 4: The fracture surface of a circular notched specimen.

The creep crack extension from a circular notched specimen is plotted against the nondimensional time as shown in Fig. 5 (a), where t_f is the life of creep crack growth (fracture time). The region of constant creep crack growth rate (CCGR) accompanied by an accelerated process of CCGR occupies the main part of the total fracture life (90%). It is different from so-called the incubation process and is a creep brittle property such as IN100[10], however CrMoV steel itself is a creep ductile material. On the other hand, in the case of CT specimen, the accelerated region of CCGR occupies the main part of the total creep fracture life as shown in Fig. 5 (b) (80%). Therefore, the creep brittle property of the circular notched specimen will be due to the effect of multi-axial stress field by a circular notch.



(a) Creep crack length of circular notched specimen. (b) Creep crack length of CT specimen.

Fig. 5: The relationship between creep crack length and the nondimensional time.

The CCGR was plotted against stress intensity factor as shown in Fig. 6. These results show that the CCGR increases with increasing in initial stress intensity factor and in temperature, and it is higher than those for CT specimens. The difference between circular notched specimen and CT specimen will be caused by the effect of multi-axial stress field due to the circular notch. As mentioned above, the constant CCGR region occupies the main part of the creep rupture life as shown in Fig.5, which corresponds to the circular region in Fig. 6. This region is defined as the first region of CCGR. Therefore, it is important to estimate the constant CCGR.

The relationship between CCGR in the first region, $CCGR_1$ and temperature is shown in Fig. 7. The results show that the CCGR is dominated by a thermally activated process. Furthermore, $CCGR_1$ is dominated by the initial stress intensity factor, K_i, as shown in Fig. 8. On the basis of these results, $CCGR_1$ of circular notched specimen is given by:

$$\left(\frac{da}{dt}\right)_i = AK_i^{14.0}\exp\left(-\frac{384.4}{RT}\right) \quad (4)$$

where Ki is initial stress intensity factor, R is gas constant (=8.314$Jmon^{-1}K^{-1}$) and T is absolute temperature. Eqn. (4) is similar as the CCGR law of IN100 alloy[10] which is creep brittle material.
On the other hand, the CCGR of CT specimen was given by[12]:

$$\frac{da}{dt} = 13.22\times10^{37}\sigma_g^{-9.626}\left(\frac{K}{70}\right)^{-34.90}\exp\left\{-\frac{304.3-363.9\ln(K/70)}{RT}\right\}, \quad (5)$$

where σ_g is gross stress. The law of CCGR of a circular notched specimen is quite different form that of CT specimen. On the basis of Eqns. (4) and (5), the following results were found out. Eqn. (5) is stress dependent thermal activated process and it is seen in creep ductile materials. However, due to multi-axial stress, CCGR behaves in creep brittle manner as shown in Eqn. (4), even though material itself is creep ductile material.

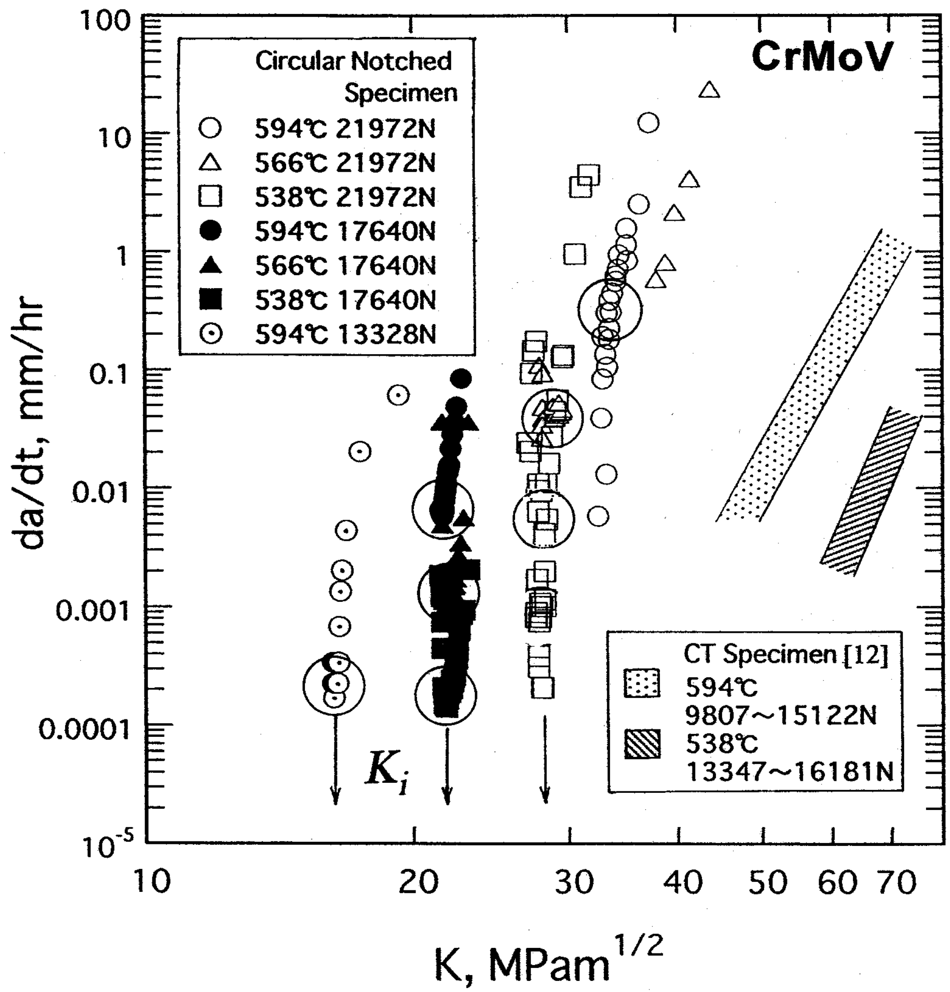


Fig. 6: Creep crack growth rate plotted against stress intensity factor

CONCLUSION

High temperature creep tests were conducted for a circular notched specimen of CrMoV steel. The electric potential drop method was adopted to measure the creep crack length. The proposed equation which relates the value of electric potential drop to crack length of a circular notched specimen was obtained.

Using this equation, the creep crack growth behaviour was investigated. The law of creep crack growth rate was derived on the basis of a thermal activation process. The law of CCGR for circular notched specimen was different from that for CT specimen and similar as that for creep brittle material, even though material itself is creep ductile. This will be caused by the effect of multi-axial stress field due to a circular notch.

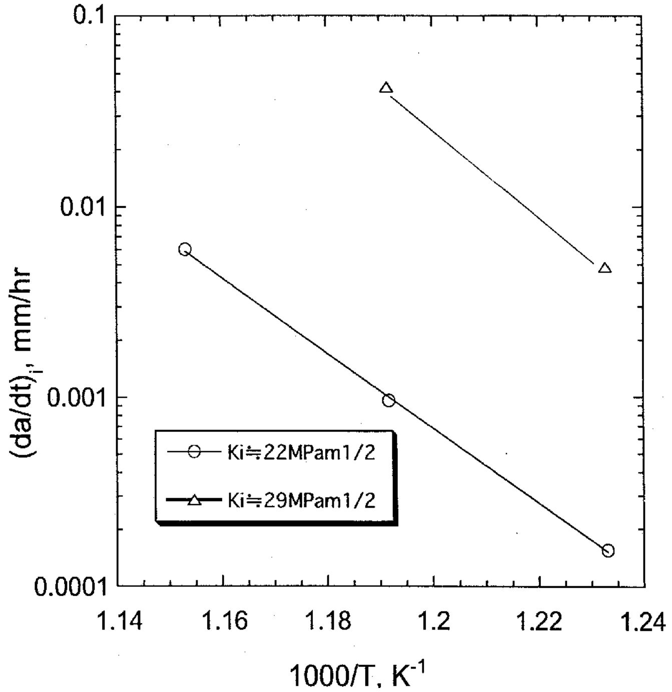


Fig. 7: The relationship between CCGR and the inverse value of absolute temperature.

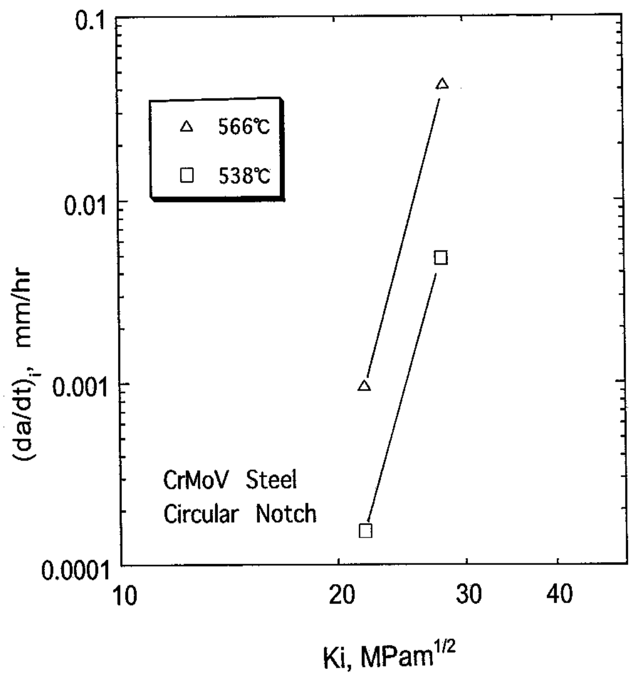


Fig. 8: The relationship between CCGR and the initial stress intensity factor.

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