THE EFFECT OF MULTI-AXIAL STRESS COMPONENT ON CREEP CRACK GROWTH RATE CONCERNING STRUCTURAL BRITTLENESS

A.T.Yokobori.Jr[1]., R.Sugiura[1], M.Tabuchi[2], A.Fuji[3], T.Adachi[4] and T.Yokobori[5]
[1]Graduate School of Engineering, Tohoku University, Aoba, Aramaki, Aobaku, Sendai City 980-8579, JAPAN
[2]National Institute for Materials Science, Independent Administrative Institution, 1-2-1 Sengen, Tsukuba City 305-0047, JAPAN
[3]Matallurgy Department, Research Institute, Ishikawajima-Harima Heavy Industries Co. Ltd, 3-1-15 Toyosu, Koto, Tokyo 135-0061 JAPAN
[4]Faculty of Science and Engineering, Ishinomaki Senshu University, Shinmito, Minamisakai, Ishinomaki City 986-8580, JAPAN
[5]School of Engineering and Science, Teikyo University, Toyosatodai 1-1, Utsunomiya City 320-8551, JAPAN

ABSTRACT

A circular notched round bar specimen produces multi-axial stress field when uni-axial stress is applied in the axial direction. This stress field is produced in practical component structure. Therefore the characterization of creep crack growth rate under this condition is important for practical use. In this paper, developed 12Cr ferritic heat resistant steel was noticed. High temperature creep crack growth tests were conducted for a circular notched specimen for 12Cr ferritic heat resistant steel. And in order to investigate multi-axial stress state of a circular notched specimen, we have conducted 3D FEM analysis. The stress multiaxiality of a circular notched specimen increased as compare with that of CT specimen. Q^* parameter which predicts creep crack growth rate is derived for this specimen. On the bases of this Q^* parameter, the algorithm of predicting the life of creep growth is proposed.

1 INTRODUCTION

Recently, since the coal fired fossil fuel power plants emit much more CO_2, NO_X, SO_X under operation, the development of the most efficient electric power plant technology is required to minimize carbon dioxide emission. Under this situation, the 12Cr ferritic heat resistant steel has been developed as boiler and turbine rotor material for most efficient electric power plant [1,2]. The fundamental mechanical properties [1] of 12Cr ferritic heat resistant steel has been clarified by the charpy impact test and tensile test using the smooth specimen. However, when these materials are used as component of a structure, cracks may occur due to the some kinds of external loads which results in failure.

Therefore, part of the authors performed the creep crack growth test using CT specimens for 12Cr ferritic heat resistant steel, and the law of creep crack growth rate and the life of creep crack growth has been obtained [3].

However, for actual component structure, the multi-axial stress field appears due to the mechanical locality of component structures such as plastic constraint in spite of applied load being uni-axial conditions, which results in structural brittleness [5]. Usually a round bar specimen with a circular notch causes such local multi-axial stress field due to plastic constrain [5].

Previously, the estimation of creep crack growth rate was conducted using a round bar specimen with a circular notch for a creep ductile material of Cr-Mo-V steel [6]. From this experimental result, the effect of multi-axial stress on the creep crack growth rate was found to cause the property of structural brittleness [6].

The Q^* parameter of a circular notched specimen for 12Cr steel was derived. The law of creep crack growth and the life of creep crack growth have been proposed [11]. In this paper, we conducted 3D FEM analysis in order to investigate the effect of multi-axial stress of circular notched specimen.

2 EXPERIMENTAL PROCEDURE

2.1 Material and Specimen

The material used is 12Cr ferritic heat resistant steel used for turbine rotor. The chemical composition and mechanical properties of this material are shown in Table 1 and 2, respectively. The geometry and size of a circular notched specimen is shown Fig.1. The circular notch is machined and notch tip angle φ equals to 60° and notch depth a_0 is 1.5mm. The stress concentration of an initial notch is 3.95 [4]. The geometry and size of CT specimen is shown Fig.2.

2.2 Test methods and testing conditions

The tests were performed using a lever arm high temperature creep testing machine. The test temperatures were kept within ±1℃. The experimental conditions are shown in figures of experimental results.

The crack length was measured by an electrical potential method. An electric current is applied to the specimen and the value of an electric potential drop is measured. The crack length is usually calculated using Johnson's equation (1) for CT, CTT, SENT and SENB specimen [7,8].

$$a = \frac{2W}{\pi}\cos^{-1}\left[\frac{\cosh(\pi y/2W)}{\cosh\left\{(u/u_0)\cosh^{-1}\left\langle \cosh(\pi y/2W)/\cos(\pi a_0/2W)\right\rangle\right\}}\right] \quad , \qquad (1)$$

where a is the length of the crack (mm), a_0 is the initial crack length (mm), y is the half length between the terminals (mm), W is the width of the specimen (mm), U_0 is the initial voltage (μm), U is the actual values of potential (μm).

However, Johnson's formula [7] may not be applied to a circular notched specimen. Thus, the crack length from a tip of a circular notched specimen is measured by an electric potential drop method using our proposed equation (2) [6,9].

For the crack extension behavior of a circular notched specimen for 12Cr steel, the crack front shows a concentric circle of which the center was almost identical with the center of the original round bar specimen with a circular notch, which is similar as that of Cr-Mo-V steel [9], as shown in Fig.3. The different of predict crack length from actual crack length was kept within 10%.

$$a = 0.667 a_0 \exp\left[0.434\frac{D}{\pi a}\cos^{-1}\left\langle\frac{\cosh(\pi y/D)}{\cosh\left\{U/U_0 \cosh^{-1}\left[\cosh(\pi y/D)/\cos(\pi a_0/D)\right]\right\}}\right\rangle\right] \quad , \qquad (2)$$

where D is the diameter of specimen (mm).

Table 1 Chemical composition of 12Cr steel

C	Si	Mn	Ni	Cr	Mo
0.09	0.02	0.53	0.51	11	0.23
W	**V**	**Nb**	**Co**	**N**	**B**
2.66	0.22	0.07	2.53	0.02	0.018

Table 2 Mechanical properties of 12Cr steel

Temp. ℃	Yied stress MPa	UTS MPa	Elongation %	R.A. %
R.T.	712	847	20	57.3
650	325	373	27.9	81.6

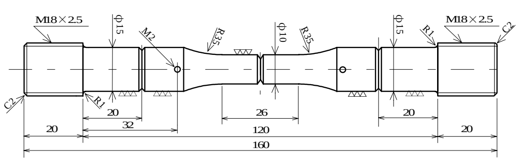

Fig.1 Geometry and size of a circular notched specimen

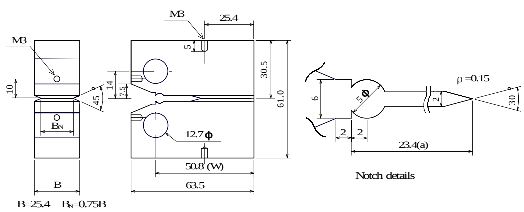

Fig.2 Geometry and size of a CT specimen

Fig.3 Fracture surface of a circular notched specimen for 12Cr ferittic heat resistant steel

3 EXPERIMENTAL RESULTS

3.1 Estimation of creep ductility using QL parameter*

The *QL**parameter is derived as a method of evaluating creep ductility [10].

The *QL** parameter is defined by equation (3).

$$QL^{*} = t_f \dot{\varepsilon}_S = M\sigma_g^m \exp\left(-\frac{\Delta H}{RT}\right) \quad , \tag{3}$$

where t_f is creep crack growth life (hr) obtained by integrating *Q** parameter, $\dot{\varepsilon}_s$ is steady state creep rate (1/hr), *M* is constant, σ_g is gross stress (MPa), *m* is exponent of gross stress, ΔHg is an activate energy (kJ/mol), *R* is the gas constant (=8.3145J/Kmol), *T* is the absolute temperature (K).

It can be seen that the logarithm values of the life of creep crack growth, t_f, has a linear relation with the logarithm values of steady state strain rate, $\dot{\varepsilon}_s$. *QL** corresponds to the values of a intercept of a linear relation at the value of log $\dot{\varepsilon}_s$ =0, and it will correspond to the creep ductility on the creep crack growth. With decreasing in *QL**, the creep ductility decreases. Each straight line does not become one and the same line. Therefore it is possible to estimate creep ductility by using the *QL** parameter as shown in equation (3) [10].

Concerning circular notched specimens and CT specimens, the logarithm values of the life of creep crack growth, t_f, were plotted against the logarithm values of steady state creep strain rate, $\dot{\varepsilon}_s$, for 12Cr steel and Cr-Mo-V steel as shown in Fig.4.

From these results for Cr-Mo-V steel, the data band of circular notched specimens falls into lower position as compare with those of CT specimens which results in decreasing *QL**. This will be due to the local multi-axial stress field induced by plastic constraint of a circular notched which is related to the structural brittleness, however applied load is uni-axial tensile condition.

On the other hand, for 12Cr steel, the data bands of circular notched specimens and CT specimens takes almost same position, and the effect of local multi-axial stress on *QL** is not so remarkable.

3.2 The effect of multi-axial stress of a circular notched specimen

In order to investigate the effect of multi-axial stress of a circular notched specimen, we conducted 3D FEM analysis using the following constitutive law,

$$\dot{\varepsilon} = A\sigma^n \quad , \tag{4}$$

where $\dot{\varepsilon}$ is creep strain rate (1/hr), values of *A* and *n of norton's law* are shown in Table 3 [12].

MSC Marc of FEM analysis code was used. The stress triaxial factor *TF* is given by

$$TF = (\sigma_1 + \sigma_2 + \sigma_3)/\sigma_{eq} \quad , \tag{5}$$

where σ_1, σ_2, σ_3 are values of principal stress and σ_{eq} is von Mises's equivalent stress.

Values of stress triaxial factor *TF* of a circular notched specimen and a CT specimen for 12Cr steel and Cr-Mo-V steel are shown in Fig.5.

From Fig.5, Value of stress triaxial factor *TF* of a circular notched specimen is much larger than that of a CT specimen both for Cr-Mo-V and 12Cr steels. This will be due to the multiaxial stress field induced by plastic constraint around a circular notch tip, which is related to the structural brittleness.

For Cr-Mo-V steel, this result corresponds to characteristics of creep ductility as shown in Fig.4.

On the other hand, for 12Cr steel, there are difference of *TF* between a CT specimen and a circular notched specimen similar as that of Cr-Mo-V steel. However, concerning creep ductility, the difference between of a circular notched specimen and a CT specimen is not so remarkable which is different from that of Cr-Mo-V steel as shown in Fig.4. This comes from following result: A circular notched specimen of Cr-Mo-V steel increases steady state creep strain rate and decreases the life of creep crack growth as shown in Fig.6. That is, property of structural brittleness appears. On the other hand, for a circular notched specimen of 12Cr steel, the life of creep crack growth doesn't shorten as compared with that of a CT specimen as shown in Fig.7 which results in creep ductilities for both a circular notched specimen and a CT specimen take the same data band. In addition, this result shows, martenstitic strengthened structure in 12Cr steel resists structural brittleness induced by *TF*.

Therefore, it is important to construct the law of creep crack growth corresponding to the lower band of creep ductility for 12Cr steel. On the basis of *Q** parameter concept, the law of creep crack growth was derived by the following equation, which assured the accuracy of life time up to 3000hr.

$$t_f = \exp\left(-44.38 - 10.93 \ln K_{in} + \frac{72.92}{T} \times 10^3 \right) \quad . \qquad (6)$$

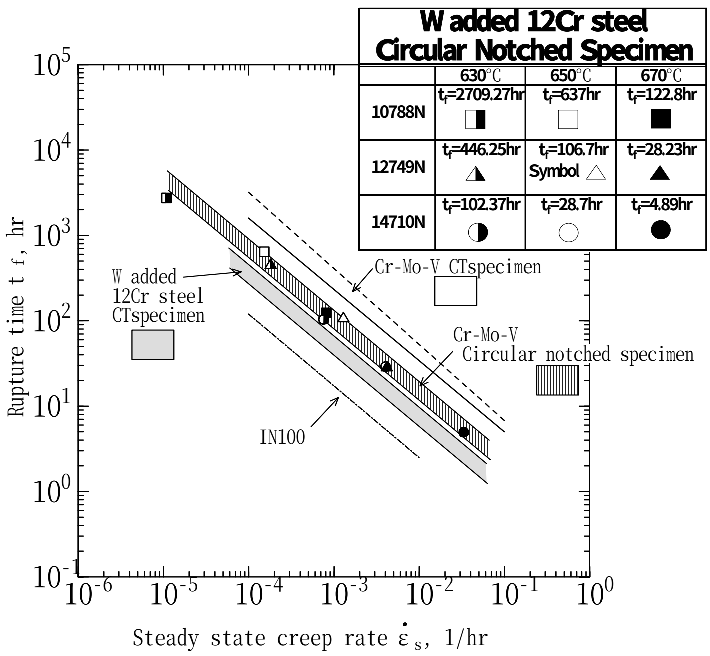

Fig.4 The relationship between the life of creep crack growth, t_f, and steady state creep strain rate, $\dot{\varepsilon}_s$, for 12Cr steel and Cr-Mo-V steel.

Table 3 Creep properties of 12Cr and Cr-Mo-V steel

	Temperature ℃	*A* $Pa^{-n}h^{-n}$	*n*
12Cr	650	1.193×10^{-42}	17.77
Cr-Mo-V	594	4.0×10^{-15}	7.06

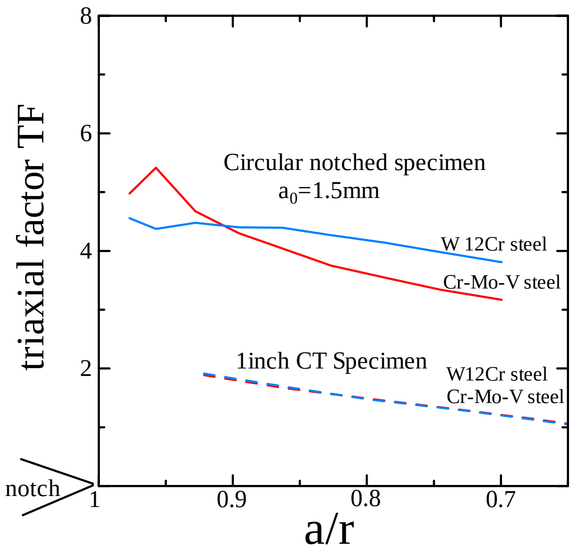

Fig.5 the stress triaxiality factor *TF* of circular notched specimens and CT specimens for 12Cr and Cr-Mo-V.

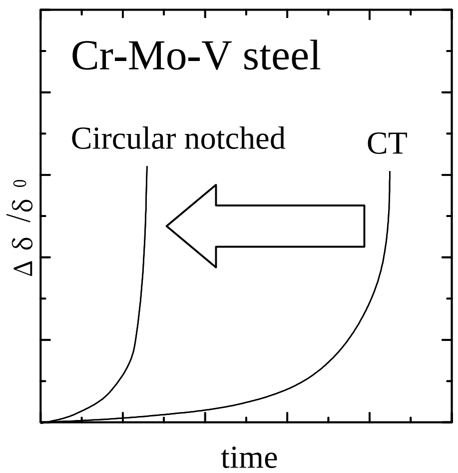

Fig.6 The relationship between creep deformation, $\Delta\delta/\delta_0$, and time of a circular notched specimen and a CT specimen for 12Cr steel.

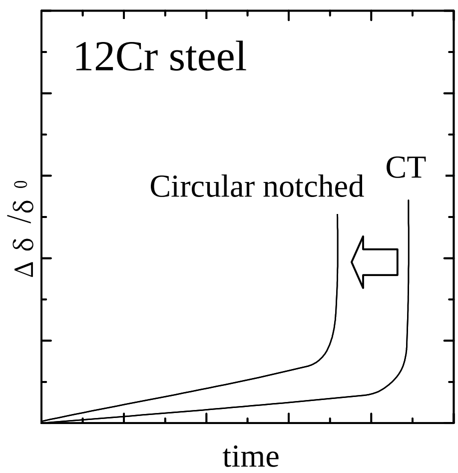

Fig.7 The relationship between creep deformation, $\Delta\delta/\delta_0$, and time of a circular notched specimen and a CT specimen for Cr-Mo-V steel.

3 CONCLUSIONS

(1) For Cr-Mo-V steel, value of stress triaxial factor *TF* of a circular notched specimen is much larger than that of a CT specimen. This will be due to the multiaxial stress induced by plastic constraint around a circular notch tip, which is related to the structural brittleness. This result corresponds to characteristics of creep ductility.

(2) For 12Cr steel, there is also difference of *TF* between a CT specimen and a circular notched specimen. However, concerning creep ductility, the difference between of a circular notched specimen and a CT specimen is not so remarkable which is different from that of Cr-Mo-V steel. This will be due to the fact that martenstitic strengthened structure in 12Cr steel resists structural brittleness induced by *TF*.

(3) It is important to construct the law of creep crack growth corresponding to the lower band of creep ductility for 12Cr steel. On the basis of Q^* parameter concept, the law of creep crack growth was derived by the following equation, which assured the accuracy of life time up to 3000hr.

$$t_f = \exp\left(-44.38 - 10.93 \ln K_{in} + \frac{72.92}{T} \times 10^3\right)$$

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REFERENCES

1. K.Hidaka, Y.Fukui, R.Kaneko and T.Fujita, I Mech Conference Transaction (1997), pp.99-113.
2. T.Fujita, Workshop on Tungsten Strengthened 9-12%Cr Heat Resistant Steels, Amagasaki, Japan, October 21 (1997).
3. A.T.Yokobori,Jr. and S.Takamori, Transaction of the annual meeting of the Japanese Society for Strength and Fracture of Materials (2000), pp.35-44 (in Japanese).
4. Peterson, R.E., Stress Concentration Design Factors John Willy and Sons (1953) pp.33
5. Takeo Yokobori, Strength and materials (Zairyou kyodogaku), Iwanami, Oct24 (1974), pp.110-111.
6. T.Adachi, A.T.Yokobori,Jr, M.Tabuchi, A.Fuji and T.Yokobori , Advances in Fracture Research, Proc. of ICF10, in the content of High Temperature Fracture of CDrom, Honolulu (2001), Eds K.Ravi-chandar, B.L.Karihaloo, T.Kishi, R.O.Ritchie, A.T.Yokobori and T.Yokobori, organized by Elsevier Sciena (2001).
7. H.H.Johnson, Materials Research and Standard, 5 (1965), pp.442-445.
8. Schwalbe,K.H and Hellman,D, Journal of Testing and Evaluation, 9, 3 (1981), pp.218-221.
9. T.Adachi, A.T.Yokobori,Jr., M.Tabuchi, A.Fuji and T.Yokobori, Material at High Temperature, Vol.20, in press (2003).
10. A.T.Yokobori,Jr, T.Yokobori, K.Yamazaki, Journal of Materials Science letters, 15 (1996), pp.2002-2007.
11. R.Sugiura, A.T.Yokobori Jr., T.Massaki, Jechang Ha and T.Adachi, Int. Con. on Advanced Technology inExperimental Mechanics (2003) CD-ROM
12. T.Yokobori, C.Tanaka, K.Yagi, M.Kitagawa, A.Fuji, A.T.Yokobori Jr. and M.Tabuchi, Results of an intercomparison of creep crack growth tests made in Japan. Mater. High Temp. (1992) 10, 2, pp.97-107