PERFORMANCE OF CREEP CRACK GROWTH ON W STRENGTHENED 9-12Cr STEEL

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ABSTRACT

This paper describes the properties of the creep crack growth in W strengthened Cr steel, newly developed for turbine rotors in ultra super critical coal fired power plant (USC). This material shows longer creep lives when compared to conventional heat resistant materials, such as SUS304 or 2.25Cr-1Mo steels. Thermal stresses induced by temperature fluctuations due to start-and-stop operation in high temperature machines and structures could be reduced due to its high thermal conductivity and low thermal expansion rate. However, since its creep ductility at rupture has been recognized as relatively low, a series of creep crack growth tests have been systemically conducted to assess the material performance controlling the initial stress intensity factor K with the use of the CT type specimen. The time rate of creep crack growth was evaluated as three parameters: stress intensity factor K, the net stress σ_{net} and C^* / creep J-integral. The minimum rate was achieved at the early stage of creep life. Although the time rate behavior changed with the test temperature and initial load, it was expressed as a function of power law during the acceleration period for each test. However, when the data were arranged using the parameters of K and σ_{net}, the coefficient in the power law depended on the temperature and the initial value of K at loading. In contrast to these, the correlation between the creep crack growth rate and C^* integral had almost the same coefficient, even when the temperature and the initial load were changed, and their relationship was plotted within a factor of two. It was also found that the creep crack growth rate was about ten times larger than that of 2.25Cr-1Mo steel at the same value of C^* integral.

1 INTRODUCTION

The design of machines and structures under elevated temperatures, *e.g.*, power generation and chemical plants, is largely dependent on the development of new advanced materials and so many kinds of new heat resistant materials have been developed to improve the performance of these plants. For example, superalloys based on nickel or cobalt have been developed for higher temperature use, and intermetalic materials for intermediate temperatures while applying characteristic properties. Moreover, a lot of new materials with controlled microstructures are also being developed. However, various kinds of verification tests are required to ensure the sound and reliable design of these high temperature plants before their practical use. Creep crack growth test is one of these essential tests. The parameter to describe the creep crack growth behavior has been discussed for a number of years, and it is suggested in general that the stress intensity factor K is preferable for creep-brittle and C^* integral for creep-ductile materials [1, 2].

A series of creep crack growth tests were performed in this paper using new ferritic steels containing W and Cr, recently developed as a candidate for turbine rotors for high efficiency, next generation power plant. The high thermal conductivity and small thermal expansion rate of this material make its use quite attractive because thermal stresses can be reduced in thin wall structures which suffer temperature fluctuations during plant operation. However, while it has been reported that this material exhibits creep-brittle behavior, the property of creep crack growth has not yet been investigated. In this paper, details of their performance are shown by completing a series of experimental tests.

Table 2.1 Chemical compositions of 11Cr-2.66W steel [mass%]

C	Si	Mn	Ni	Cr	Mo	V	W	Nb	Co	B	N	Fe
0.09	0.02	0.53	0.51	11.0	0.23	0.22	2.66	0.07	2.53	0.018	0.020	Bal.

Heat treatment: Quench; 1050°C O.Q., Temper;570°C A.C. + 720°C A.C.

Table 2.2 Mechanical properties of 11Cr-2.66W steel

Temp. [°C]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	Elong. [%]	R.A. [%]
R.T.	712	847	20.0	57.3
600	465	517	29.0	80.4
625	414	440	27.1	81.9
650	325	373	27.9	81.6

2 EXPERIMENTS

2.1 Test materials and specimens

The material employed was 11Cr-2.66Cr steel, which has been recently developed by Hitachi Ltd for a USC turbine rotor. Table 1 shows the chemical compositions. The main additives to the composition are Cr and W. This ferritic steel features good performance in terms of both the high temperature strength and physical properties. Thus, it could be applied to components in the power plant thats must have frequent start-and-stop procedures during their service lives. Furthermore both machine processing and welding are achieved easily, so that it could be applicable to wide range of components in large-scale machines and structures.

All specimens for tensile, creep, and creep crack growth tests were machined from a trial fabricated rotor which had an inner diameter of 150mm, an outer diameter of 420mm, and which weighed 200 kN. The directions of tensile and crack propagation coincided with the radial direction of the rotor. The specimen used for the crack propagation test was the standard compact tension (CT) type which had a thickness of 25.4mm (1 inch) and a depth of 50.8mm (W). Side grooves in the CT specimen were machined to promote uniform crack extension across the thickness of the specimen after a pre-fatigue crack of about 3 mm in length was introduced at the condition of K = 16MPam$^{0.5}$ which was a magnitude much lower than those in the creep crack growth tests. Thus, the specimen configuration had a planar dimensional proportionality with an initial crack size a_o, such that a_o/W= 0.508.

2.2 Testing conditions

Testing machines used were dead weight loading type with lever ratios of 1:10 for creep and 1:40 for creep crack growth tests. Electric furnaces were employed and all the tests were conducted in the air. Temperature fluctuations during the test were kept within +/-0.5°C. Since the material tested was originally designed for the use at a temperature of 650°C and a pressure of 35MPa, test temperatures in this paper were set at 600°C, 625°C, and 650°C. Four loading levels were selected to examine the influence of the magnitude of load on the property of creep crack growth, where K = 28, 31, 34, and 37MPam$^{0.5}$.

2.3 Creep crack growth tests

The constant weight was loaded by pin in tension during the tests. Testing loads were calculated to produce the initial stress intensity factors K of generated values. The crack length performed due to creep was detected continuously using the electrical potential drop technique, where 5A was sup-

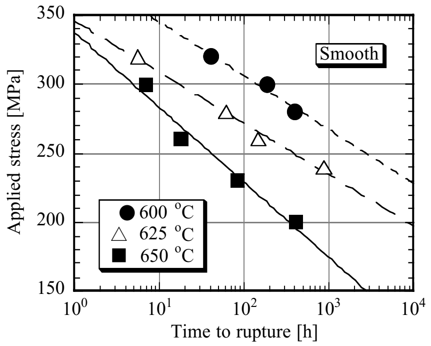

Fig.1 Relationship between time to rupture and applied stress under uni-axial creep tests

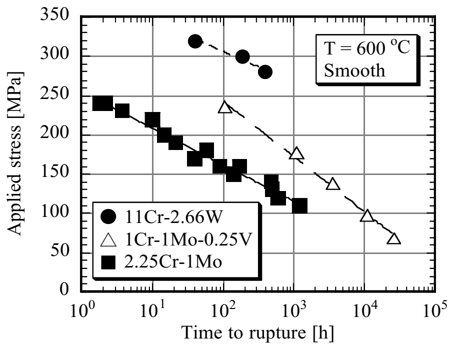

Fig. 2 Comparison of time to rupture with other heat resistant materials

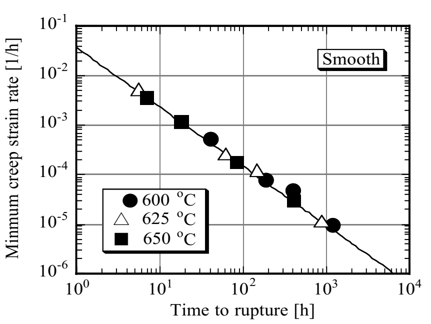

Fig.3 Relationship between time to rupture and minimum creep strain rate under uni-axial creep tests

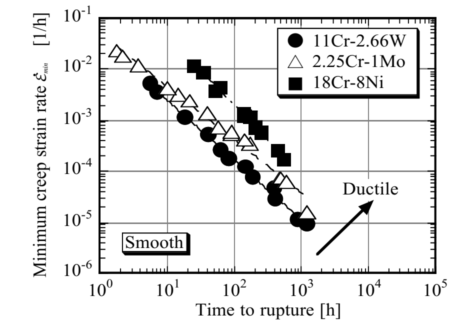

Fig.4 Monkman-Grant's relationship for heat resistant mateials

plied as the input direct current. The Johnson's equation was employed to convert the output voltage into crack length [3]. At the same time a deflection between the loading pins was measured by using a pair of linear gages with an accuracy of 2.5μm, and recorded in a *X-t* recorder together with the crack length. Specimens were fractured in room temperature due to fatigue after the completion of tests. Only when the final crack length measured on the fracture surface coincided with the one electrically measured to within an accuracy of 0.1 mm was the data on the creep crack length accepted as the results of the creep crack growth test. The creep crack growth rate was evaluated in terms of parameters K, σ_{net}, and C^* integral as discussed in the next chapter.

3 RESULTS AND DISCUSSION

3.1 Creep properties

Figure 1 shows the creep rupture data, which exhibits little scatter over the range of testing temperatures. The elongations at rupture were around 20%, with a reduction of area 80% for all the specimens. These data were independent of the temperature and the initial stress. The creep ductility was relatively low, but still had enough ductility to apply to high temperature components. A relationship between the applied stress and the minimum creep rate was well described using Norton's law. Indices in this power law were used to calculate C^* integral hereafter. In Fig.2 the time to rupture of the material is compared with other conventional ferritic steels at 600°C, *e.g.*, 1Cr-1Mo-0.25V and 2.25Cr-1Mo steels [3,4]. It was seen that the creep life of 11Cr-2.66W steel was 10 to 100 times longer than those of the other two materials at the same stress. This reveals that the test material has a great

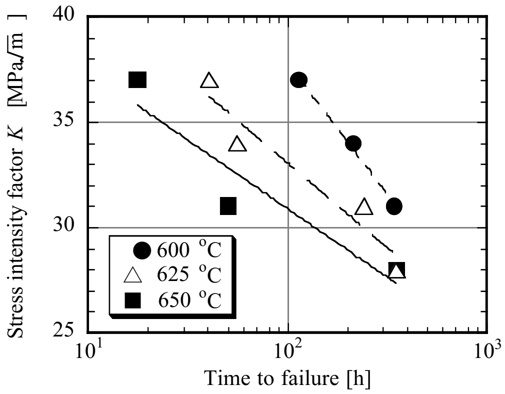

Fig.5 Relationship between time to failure and stress intensity factor in creep crack growth tests.

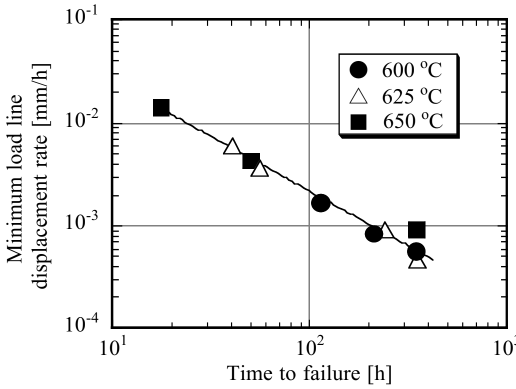

Fig.6 Relationship between time to failure and minimum loadline displacement rate in creep crack growth tests.

advantage in terms of the creep strength at rupture.

The minimum creep rate is plotted against the time to rupture in Fig.3, and it was found that all the data fit on a single line in spite of the different test temperatures. This relationship implies that the rupture would occur whenever the creep strain due to the steady creep reaches a certain value, and its intercept depends on the creep ductility [5]. The Monkman-Grant relationship obtained from other conventional heat resistant materials are also drawn in Fig.4 to compare the creep ductility at rupture with the test material. It is shown that although 11Cr-2.66W steel has longer creep lives than other materials at the same stress, its creep ductility is inferior to conventional materials. Thus, collecting the creep crack properties of these new materials will be important to enable designers to apply them into actual high temperature components.

3.2 Creep crack growth

When the material has enough ductility and the width of CT specimen employed is thick, the so-called tunneling phenomenon sometimes occurs along the crack tip during the process of creep crack propagation. After completing creep crack growth tests, the actual length of creep crack developed in the ligament was measured using a microscope. Owing to the side grooves on the CT specimen, the crack tip almost developed smoothly towards the uncracked ligament. The SEM observation around the crack tip did not reveal any existence of creep voids and/or cavities because of ductile deformation near the crack tip.

Figure 5 shows the time to failure in the creep crack growth test. The stress intensity factor K calculated from the initial load was expressed as a logarithmic function of time to failure for every temperature. The time to failure depends on the temperature, especially at higher levels of the stress intensity factor. The minimum rate of load line displacement was achieved in the middle of the entire life, and the relationship between them is expressed as a single power law in Fig.6. This is almost the same relation as in Fig.3. This means that a measurement of the minimum load line displacement can predict its failure time as long as the material has good creep ductility.

3.3 Characterization of creep crack growth rate

The rate of creep crack growth against time (da/dt) can be represented in a similar manner to the creep rate in creep tests, and it reaches a minimum value at an early stage of life. The rate da/dt was evaluated for every temperature and every load using three parameters; the stress intensity factor K,

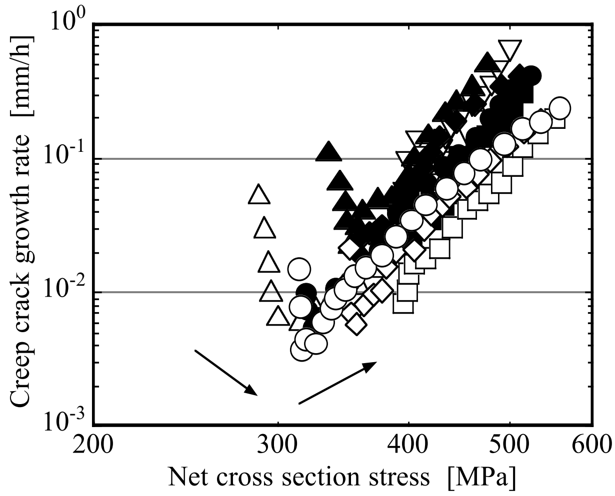

Fig.7 Evaluation of the creep crack gwoth rate on net cross section stress. Symols means the same in Fig.8.

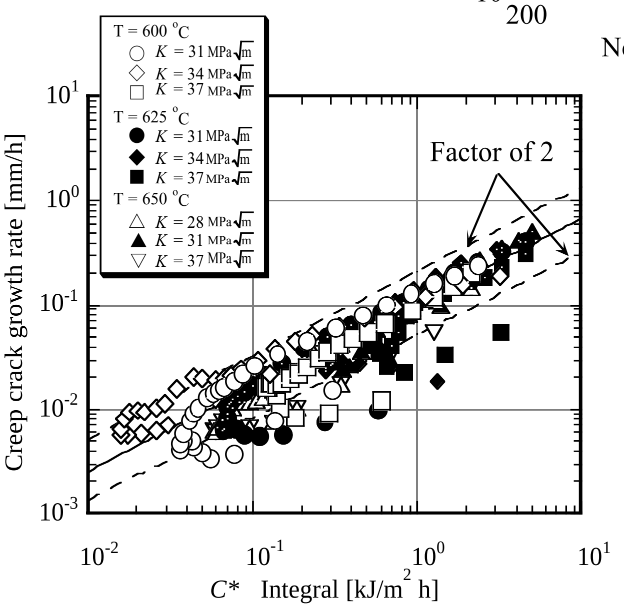

Fig.8 Relationship between creep crack growth rate and C^* parameter.

the net cross section stress σ_{net}, and C^* integral.

Firstly, the rate da/dt was expressed as a power law for the most accelerated stage of life when using K parameter. However, it has a strong dependency on the test temperature at the same load in spite of the limited range of temperature, because K is the correlating parameter developed for brittle materials. Another similar correlation existed between da/dt and the net cross section stress σ_{net} shown in Fig.7. Although the scatter band of data becomes narrower than those plotted against K, a temperature dependency is also observed. Lastly, all the data plotted against the C^* integral are shown in Fig.8. In this case, a tail portion appears at the early part of the life, and it varies with test conditions; temperatures and stress intensity factors K calculated by initial loads. However, da/dt can be expressed as a power law of Eqn.(1) for the acceleration stage of life, and almost all data are plotted within a factor of two around the solid mean line. The C^* integral has been used to characterize the local stress-strain rate fields around the crack front in a body subjected to extensive creep conditions. There was little evidence of brittle fracture in the fracture surface, and as a result, C^* integral would

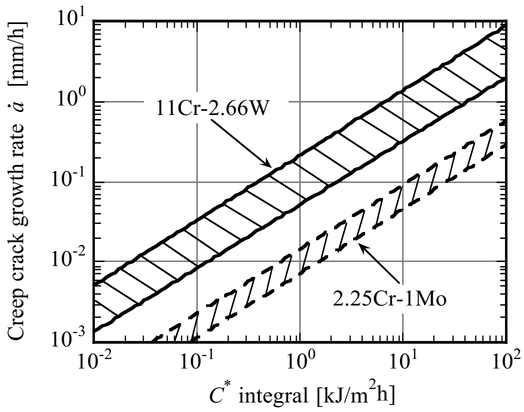

Fig.9 Comparison of creep crack growth property between 11Cr-2.66W and 2.25Cr-1Mo steels

be the best parameter to describe the behavior of creep crack growth among the three parameters examined here, such that:

$$da/dt = 0.1017C^{*0.589} \quad (1)$$
$$(da/dt : \text{mm/h}, \; C^{*}: \text{kJ/m}^2\text{h})$$

The property of creep crack growth characterized by C^* integral are compared in Fig. 9, where the test temperature for 2.25Cr-1Mo steel is 550°C. Although this temperature was lower than the tests on 11Cr-2.66W steel, the creep crack in 11Cr-2.66W steel grew about ten times faster at the same value of C^* integral than that for 2.25Cr-1Mo steel [6]. Thus, despite the fact that the creep rupture strength of 11Cr-2.66W steel was superior to the other conventional materials, much more data would be required in the practical use of 11Cr-2.66W steel to establish the safety and reliability of high temperature components.

4 CONCLUSIONS

New heat resistant materials have been developed to achieve higher performances at elevated temperatures. The 11Cr-2.66W ferritic steel is one of them, which has developed for a turbine rotor in USC. However as yet, its creep crack growth properties have not fully been examined. Thus before its practical application, several tests were carried out employing CT specimens. The creep crack growth rate was evaluated using three parameters: the stress intensity factor K, the net cross section stress σ_{net}, and C^* integral. The following conclusions were obtained; (1) The test material would have about ten to one hundred times the creep rupture strength compared to conventional materials. (2) Creep crack growth accelerated during most of the life and its rate was well evaluated using a power law of C^* integral. (3) The acceleration rate is ten times faster than that of 2.25Cr-1Mo steel.

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