The Effects of Strain Rate and Number of Cycles on Creep Damage during Relaxation Periods in LCF Tests

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ABSTRACT

A ductility exhaustion method, coupled with a creep constitutive equation, was applicable to evaluate a creep damage during hold period in low cycle fatigue of Hastelloy XR at elevated temperature.

1 INTRODUCTION

Creep-fatigue life evaluation is one of the main subjects of structural design work at elevated temperatures. In a high-temperature gas-cooled reactor, the structural components are enforced to severe thermal exposure in a primary and a secondary coolant systems. A typical component is a heat exchanger located at the boundary between the primary and the secondary coolants. The heat tubes and the center pipe are designed to be used, for example, at the maximum temperature of 950°C in the HTTR. The installation of structural components into a creep regime of the materials requires us to establish the creep constitutive equation in order to calculate the history of stress and strain in operation. According to the inelastic stress analyses of high temperature components of the intermediate heat exchanger in the JAERI, thermal stress induced by the temperature difference is to be limited within an elastic-creep regime in an normal operation. And stress relaxation occurs at peak stress area near the surfaces of center pipe and heat tube.

Hitherto a time fraction rule is used widely to estimate the creep-fatigue life in the design work of advanced reactors as well as conventional ones, and the results show the large dependence of the estimated life time on strain rates in laboratory tests of Hastelloy XR. We discussed the applicability of the ductility exhaustion method[1,2] with changing the strain rate before a hold period.

2 CREEP DAMAGE EVALUATION

At elevated temperatures the creep constitutive equation is required to calculate creep strain and stress of components precisely. Conventionally the time fraction rule is used to evaluate the creep damage of the structural components by the next equation,

$$D_t = \Sigma \frac{\Delta t}{T_r} \qquad (1)$$

where Dt: creep damage in the time fraction rule, Δt: time duration at applied stress level of σ, Tr: time to rupture at applied stress level of σ. The es-

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tablishment of the creep constitutive equation, however, means that we have an alternative method to evaluate the creep damage measured by strains at failure. It is called as a ductility exhaustion method and described by the next equation,

$$D_d = \sum \frac{\Delta \varepsilon^c}{\varepsilon^c_r} \tag{2}$$

where Dd: creep damage in the ductility exhaustion method, $\Delta\varepsilon^c$: creep strain increment at applied stress level of σ, ε^c_r: failure strain at applied stress level of σ. In this method the value of the ductility exhaustion is affected by the creep constitutive equation and the definition of ductility at failure. Especially a primary creep is sensitive to calculate the creep strain rate in the applied stress levels which is to be expected not so high in the design work, because of mainly taking thermal exposure.

3 EXPERIMENT

Low cycle fatigue tests were conducted at 950°C in vacuum of 10^{-4}Pa by electrohydraulic testing machine controlled by a computer. The specimens as shown in Fig.1 was heated up by the induction coil. The axial strain of specimens with 8mm in diameter was controlled by the extensometer between the gauge length in 15mm. A strain range is kept at 0.1% and a strain rate is changed to 0.05, 0.01 and 0.001%/s. A hold time period is also kept in 300s. A fatigue test was carried out at nearly the same strain rate with the fastest one with the hold period. The applied load was measured and stocked to computer memory. The material, which is a Ni-based super alloy called Hastelloy XR, was developed to improve the corrosion resistance and creep strength in the simulated-helium gas environments for the HTTR. Table 1 shows a chemical compositions. Material was hot-forged, taken a solution annealing at 1190°C and then cooled rapidly.

Constant stress creep tests were done by a balanced weight inside an electric-heated furnace at 950°C in air. Creep specimenis a bar type with 6mm in diameter and 30mm in gauge length as shown in Fig.2. Tests were carried out under the assumption of invariable volume within the gauge length measured by a extensometer. The stress range is24 to 120MPa. Furthermore the constant stress test at 150MPa is attached to obtain a reduction of area and an elongation at failure.

Table 1 Chemical compositions of Hastelloy XR

C	Mn	Si	P	S	Cr	Fe	Mo	W	Co	B	Al	Ti
0.07	0.95	0.33	<0.001	<0.001	21.98	18.61	9.11	0.49	0.03	0.0002	0.02	0.01(wt%)

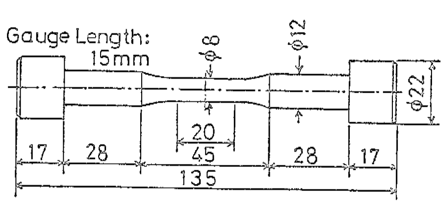

Fig.1 Specimen in low cycle fatigue test

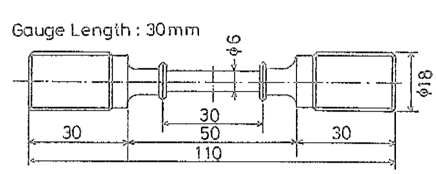

Fig.2 Specimen in creep test

4 EXPERIMENTAL RESULTS

4.1 Low cycle fatigue tests

The relationship between the number of cycles and the stress range is shown in Fig.3, where σ max is peak stress at tension, σ min is peak stress at compression and σi is residual stress at the end of the hold period. Materials show a cyclic hardening slightly at the first stage of cycles except for the case at 0.001%/s. Then they softened with increasing the number of cycles. The range of stress relaxation during the hold period became stable after about ten cycles. The number of cycles at failure was more than 10^5 in the case of without the hold period.

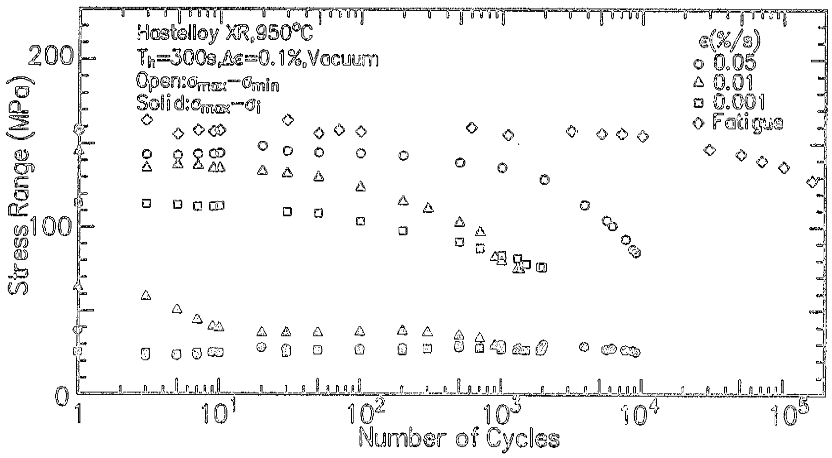

Fig. 3 Number of cycles vs. stress range

4.2 Creep tests

Figure 4 shows the relationship between creep strain and time. A next creep constitutive equation was established for the further analyses of creep deformation.[3] A primary creep was described as a exponential term and a secondary creep as Norton's law.

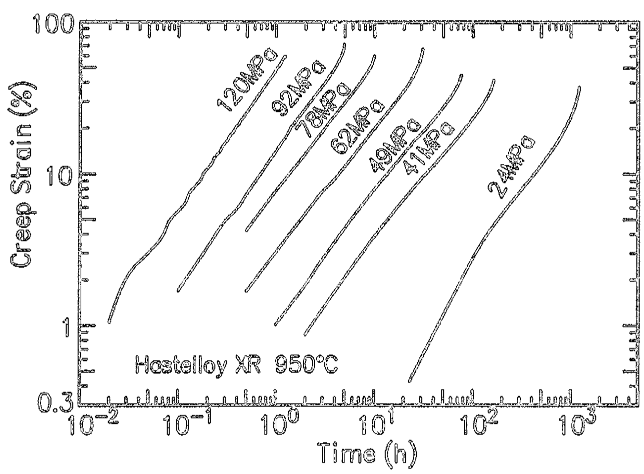

Fig. 4 Creep curves

$$\varepsilon^c = \varepsilon_t \{1 - \exp(-rt)\} + \dot{\varepsilon}_m t , \tag{3}$$

$$\varepsilon_t = 4.35 \times 10^{-2} \exp(0.00460\sigma) , \tag{4}$$

$$r = 5.35 \times 10^{-3} \exp(0.0575\sigma) \tag{5}$$

and

$$\dot{\varepsilon}_m = 3.30 \times 10^{-11} \sigma^{4.35} \tag{6}$$

where σ is applied stress(MPa), ε^c is creep strain and t is time(h).

Strains at rupture were measured by the elongation and the reduction of area as shown in Fig.5. Considering that all tests were done by controlling the gauge lengths, the strain at rupture defined by the elongation experimentally was applied to evaluate the ductility exhaustion. In this figure the strain at rupture calculated by the next relation was also shown.

$$\varepsilon^c_r = \int_0^{T_r} \dot{\varepsilon}_m dt \tag{7}$$

The strain at rupture given by the elongation at failure was slightly high than that given by the above relation because of the primary and tertiary creeps.

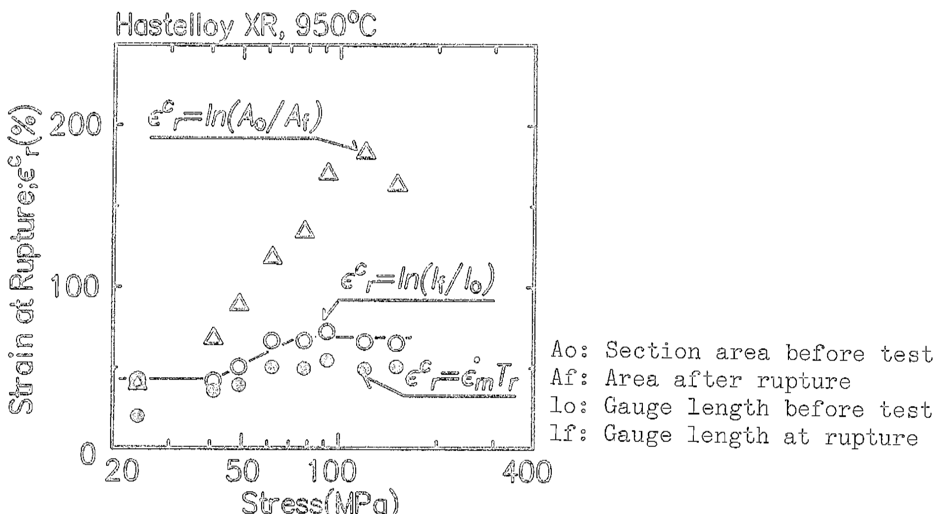

Fig.5 Strain at rupture

Time to rupture was given by the next equation.

$$T_r = 1.07 \times 10^9 \sigma^{-4.25} \tag{8}$$

5 RESULTS AND DISCUSSION

Figures 6, 7 and 8 show the relaxation profiles at various strain rates. It is noticed that the profiles are very affected by the strain rates before the strain hold period. The initial stresses σ_o at the strain rate of 0.001%/s are nearly equal to those of 0.01%/s but the profiles at the faster strain rate shows a rapid stress reduction at the first moment of the strain hold period. This tendency becomes more clear in the stress states at the strain rate of 0.05%/s; the stress relaxed within a minute and then the residual stress was gradually decreasing. Table 2 shows the amount of creep strains accumulated during the hold period in a cycle. One is calculated by the next equation.

$$\Delta\varepsilon^c = \int_{hold} \dot{\varepsilon}^c dt \tag{9}$$

The creep strain rate $\dot{\varepsilon}^c$ at the stress σ is given by the eqn.(3) and the next equation under the assumption of strain hardening law.

$$\dot{\varepsilon}^c = r\,\varepsilon_t \exp(-rt) + \dot{\varepsilon}_m \tag{10}$$

Table 2 Creep strain during strain hold period

$\dot{\varepsilon}$ (%/s)		N=10	N=100	N=500
0.001	Cal.	2.02×10^{-2}	1.43×10^{-2}	8.77×10^{-3}
	$\Delta\sigma$/E	2.09×10^{-4}	2.22×10^{-4}	2.47×10^{-4}
0.01	Cal.	5.72×10^{-3}	5.84×10^{-3}	4.24×10^{-3}
	$\Delta\sigma$/E	3.31×10^{-4}	3.11×10^{-4}	2.94×10^{-4}
0.05	Cal.	1.36×10^{-2}	5.12×10^{-2}	4.79×10^{-3}
	$\Delta\sigma$/E	2.09×10^{-4}	2.29×10^{-4}	2.37×10^{-4}

Cal.: Calculated by creep constitutive equation,
$\Delta\sigma$: Stress reduction range,
E: Young's modulus 120GPa and
N: Number of cycles

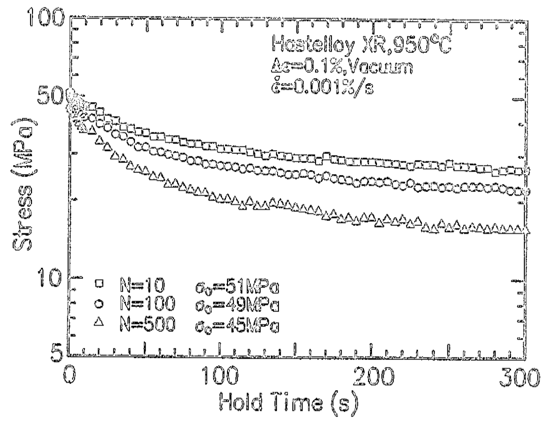

Fig. 6 Relaxation profile at $\dot{\varepsilon}$=0.001%/s

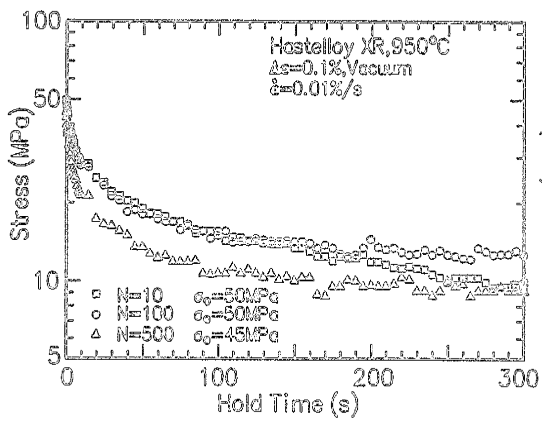

Fig. 7 Relaxation profile at $\dot{\varepsilon}$=0.01%/s

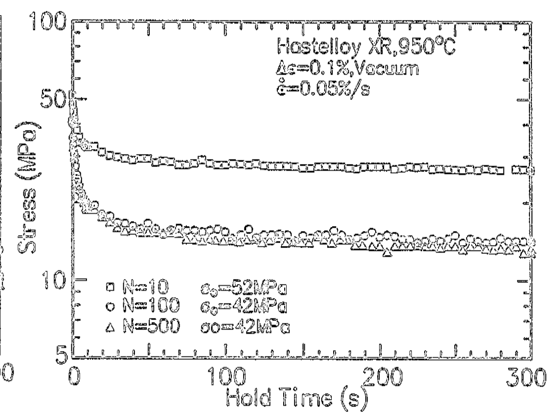

Fig. 8 Relaxation profile at $\dot{\varepsilon}$ =0.05%/s

The other one is obtained by the next relation,

$$\Delta \varepsilon^c = \frac{\Delta \sigma}{E} \tag{11}$$

assuming that an elastic strain is transformed to creep strain uniformly. The calculated creep strains during the hold period showed a larger value than those obtained by stress reduction ranges.

The definition of failure was not clear to describe in the experiment. Each of specimens showed cracking on their surface in the SEM observation as given by Fig.9. The depths of surface cracking are one grain size and no cracking was observed inside the specimen as shown in Fig.10. However, the number of cycles to failure was defined by 25% in the stress range reduction from a stable state which appeared at the cycles during 10 to 100. Table 3 shows the number of cycles to failure and the creep damage evaluated by the ductility exhaustion as well as the conventional time fraction. The creep damage during the hold period is counted up to the failure cycles from the first one. It could be noticed that the ductility exhaustion method is applicable to evaluate the life of Hastelloy XR in the creep regime because it estimates the creep damage more precisely than the time fraction rule.

Table 3 Creep damage at failure

$\dot{\varepsilon}$(%/s)	Dd	Dt	Nf
0.001	0.414	0.129	1950
0.01	0.103	0.013	920
0.05	0.503	0.032	5000

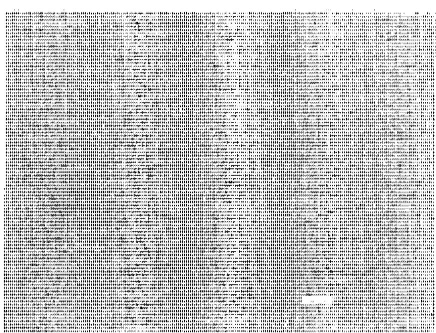

Fig.9 Specimen surface

Surface

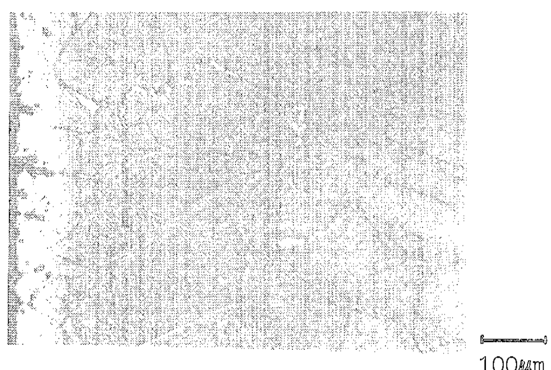

Fig. 10 Micro-structure

* Axial direction is top-bottom and strain rate is 0.01%/s in Figs.9 & 10.

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