Creep Properties of Hastelloy X and Their Application to the Structural Design*

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Synopsis

In the creep curve of Hastelloy X, it was difficult to divide it into the three stages of creep. However, these stages were made distinguishable by plotting the relationship between creep rates and time in double-logarithmic coordinates.

All the creep data of Hastelloy X, except the isochronous stress-strain curves, required for determining the design stress intensities S_0 and S_t were arranged through the Larson-Miller parameter. The isochronous stress-strain curves for a heat of Hastelloy X were derived from the constitutive equations obtained from short-term data. A fairly good agreement between the predicted data and the experimental data was obtained.

I. Introduction

In the development of the Very High Temperature Gas-cooled Reactor (VHTR), it has become necessary for the elevated temperature structural design to accumulate the creep data of materials used to the reactor. In particular, it is necessary to construct the isochronous stress-strain curve which is used for establishing design stress intensities and for performing creep-fatigue interaction analyses.

In this investigation, creep and stress rupture tests up to about 3 000 hr duration on three heats of Hastelloy X which is one of the materials considered for use in VHTR were carried out at 800°, 900° and 1 000°C. By analyzing the observed creep properties, the constitutive equations of creep in the primary and the secondary creep stages for a heat of Hastelloy X were proposed and the isochronous stress-strain curves were constructed by using these equations. Moreover, creep data, except the isochronous stress-strain curve, required for the elevated temperature structural design such as stress *vs.* rupture time, stress *vs.* secondary creep rate, and stress *vs.* time to initiation of tertiary creep were arranged through the Larson-Miller parameter.

II. Materials and Test Procedures

Three heats of Hastelloy X having different manufacturing processes were used for this study. Those manufacturing processes, chemical compositions, and mechanical properties are shown in Table 1.

All specimens were machined to 6 mm gage diameter and 30 mm gage length in the rolling direction from the 15 mm thick plates. The surface finish for all the cases was as-milled. The surface roughness along the gage length was about 6 μ . Its geometry is shown in Fig. 1.

Creep and stress rupture tests based on JIS Z2271

were performed in air at 800°, 900° and 1 000°C using lever type creep testing machines with a 10 to 1 lever ratio. The temperature of the specimen was monitored by means of three calibrated 13%PR thermocouples placed along the gage length. The temperature along the gage length was kept within $\pm 3^\circ\text{C}$. Elongation of the specimen was measured by means of two dial gages attached to the gage length of the specimen. The dial gage can be read to an accuracy of 1/100 mm. Elongation measurements were generally made twice daily until the specimen failed.

III. Results and Discussion

1. Creep Curve

Typical creep curves obtained for each heat of Hastelloy X at 900°C are shown in Fig. 2. From this figure, remarkable differences of creep resistance among the three heats of Hastelloy X are seen. This tendency was also seen at 800° and 1 000°C. It appears that the differences of creep resistance among the three heats of Hastelloy X depend mainly on grain size variation. The grain size of HAEN is larger than those of the others as shown in Table 1. It is then

Fig. 1. Geometry of test specimen

Fig. 2. Creep curves for Hastelloy X measured at 900°C

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Table 1. Chemical compositions and mechanical properties of

Material	Mark	Thick- ness (mm)	Melt- ing pro- cess	Final heat treatment	Grain size	Chemical composition (%)								
						C	Si	Mn	P	S	Ni	Cr	Co	Mo
Hastelloy X	HAEN	15	AE	1 120°C× 18 min W.Q.	ASTM No. 1~4	0.087	0.47	0.85	0.018	0.003	Bal.	21.61	1.53	9.00
	HVEN		VE		ASTM No. 1~6	0.086	0.22	0.75	0.009	0.002	Bal.	21.47	1.60	8.80
	HAEM		AE	1 150°C× 50 min W.Q.	ASTM No. 5~6	0.07	0.34	0.60	0.010	≤ 0.005	Bal.	20.84	1.03	8.98

* AE: Air melting followed by electroslag remelting
VE: Vacuum induction melting followed by electroslag remelting

considered that the creep resistance of HAEN is superior to those of the other heats.

The primary, secondary and tertiary creep stages are not clear in the creep curves obtained from the present tests. Therefore, it is difficult to determine the initiation of secondary and tertiary creep from these curves.

2. Creep Rate Curve

The creep rate was plotted against time in double-logarithmic coordinates to clarify three stages of creep. Examples of creep rate curves obtained for HAEN are shown in Fig. 3. Creep rate at arbitrary time, $\dot{\epsilon}_n$, was calculated as follows:

$$\dot{\epsilon}_n = \frac{\epsilon_n - \epsilon_{n-1}}{t_n - t_{n-1}} \dots\dots\dots(1)$$

where, t_n : Creep time till the elongation measurement of (n)th time
 t_{n-1} : Creep time till the elongation measurement of (n-1)th time
 ϵ_n : Creep strain at t_n
 ϵ_{n-1} : Creep strain at t_{n-1} .

In Fig. 3, a region where the creep rate decreases as time increases, a region where the creep rate is constant regardless of time, and a region where the creep rate increases as time increases are the primary, the secondary and the tertiary creep stages, respectively. Thus, three stages of creep for Hastelloy X can be separated relatively easily by plotting the creep rate against time in a double-logarithmic coordinates.

3. Relation between the Primary Creep Rate and the Secondary Creep Rate

It has been confirmed in carbon steel that if the primary creep rate, $\dot{\epsilon}_1$, and the secondary creep rate, $\dot{\epsilon}_{min}$, are expressed by Eqs. (2) and (3), and Eqs. (4) and (5) hold, then Eq. (6) holds at an arbitrary time and stress.^{1,2)}

$$\left. \begin{aligned} \dot{\epsilon}_1 &= n\beta_0\sigma^m t^{n-1} \\ \dot{\epsilon}_{min} &= K_0\sigma^{m'} \end{aligned} \right\} \dots\dots\dots(2)$$

$$\left. \begin{aligned} \dot{\epsilon}_1 &= A \exp\left(-\frac{K}{T}\right) \\ \dot{\epsilon}_{min} &= A' \exp\left(-\frac{K'}{T}\right) \end{aligned} \right\} \dots\dots\dots(3)$$

Fig. 3. Creep rate curves for a heat of Hastelloy X (HAEN) measured at 900°C

$$\frac{m}{m'} \cong \text{constant}, \quad n\beta_0 K_0^{-m/m'} \cong \text{constant} \dots\dots(4)$$

$$\frac{K}{K'} = \frac{m}{m'} \cong \text{constant} \dots\dots\dots(5)$$

$$\dot{\epsilon}_1 \times \dot{\epsilon}_{min}^{-m/m'} = n\beta_0 K_0^{-m/m'} t^{n-1} \dots\dots\dots(6)$$

where, σ : applied stress
 t : creep time
 T : absolute temperature
 n, β_0, m, K_0, m' : constant
 A : function of time and applied stress
 A', K, K' : function of applied stress

The initial applied stress *vs.* the primary creep rate ($t=5$ hr) and the secondary creep rate in double-logarithmic coordinates for three heats of Hastelloy X are plotted in Figs. 4 and 5 respectively. From these figures, linear relationships between those creep rates and the applied stress are observed.

Temperature dependence of m, m' and m/m' for HAEN obtained from Figs. 4 and 5 is shown in Fig. 6. Constants m and m' are found to change lineally with the reciprocal of absolute temperature within the temperature range of the present tests. Moreover, as shown by Eq. (7), m/m' was found to be constant regardless of temperature, *i.e.*:

$$\frac{m}{m'} \cong 0.37 \dots\dots\dots(7)$$

The relationship between the two constants β_0 and K_0 for HAEN plotted in double-logarithmic coordinates is shown in Fig. 7. The linear relationship

materials used

W	B	Fe	Mechanical properties			
			0.2% P.S. (kg/mm ²)	T.S. (kg/mm ²)	El. (%)	R of A (%)
0.40	0.0029	18.83	30.4	71.1	59.0	65.0
0.50	0.0037	17.97	34.3	73.8	49.3	56.9
0.54	0.0020	18.22	38.7	75.0	47.6	—

Fig. 4. Relation between primary creep rate ($t=5$ hr) and initial applied stress

Fig. 5. Relation between secondary creep rate and initial applied stress

exists between the constants β_0 and K_0 , and from this figure the gradient of this curve is found to be calculated as 0.38. This value is nearly equal to the value of m/m' . Meanwhile, as shown in Fig. 8, constant β_0 changed linearly with the reciprocal of absolute temperature within the temperature range of the present tests. The constant n can be calculated from the gradient of the curve at the primary creep stages shown in Fig. 3, that is,

$$n = 0.41 \quad \text{.....(8)}$$

Fig. 6. Temperature dependence of $m, m', m/m'$ for Hastelloy X (HAEN)

Fig. 7. Relation between β_0 and K_0 for Hastelloy X (HAEN)

Fig. 8. Temperature dependence of β_0 for Hastelloy X (HAEN)

This value was independent of stress and temperature so far as the present tests were concerned. From the above-mentioned results, Eq. (9) is given.

$$n\beta_0 K_0^{-m'm'} = 0.287 \quad \text{.....(9)}$$

The relationship between the primary and secondary creep rates obtained at 800°, 900° and 1000°C for HAEN is shown in Fig. 9. From this figure, a linear relationship between the primary and secondary creep rates is observed regardless of temperature within the range of the present tests, that is, it is considered that Eq. (6) holds for Hastelloy X in the present tests. Equation (5) could not be proved directly from the results of the present tests. It is, however, considered

Fig. 9. Relation between primary creep rate and secondary creep rate for Hastelloy X (HAEN)

T : Absolute temperature ($^{\circ}\text{K}$)
 t_r : Time to rupture (hr)

Fig. 10. Larson-Miller plots of stress vs. time to rupture data for Hastelloy X

T : Absolute temperature ($^{\circ}\text{K}$)
 $\dot{\epsilon}_{\min}$: Secondary creep rate (%/hr)

Fig. 11. Larson-Miller plots of stress vs. secondary creep rate data for Hastelloy X

that Eq. (5) is expected to be established also for Hastelloy X, because Eqs. (4) and (6) are established for Hastelloy X.

4. Larson-Miller Plots

Larson-Miller plots of stress vs. time to rupture,

T : Absolute temperature ($^{\circ}\text{K}$)

t_{2nd} : Time to initiation of secondary creep (hr)

Fig. 12. Larson-Miller plots of stress vs. time to initiation of secondary creep data for Hastelloy X

T : Absolute temperature ($^{\circ}\text{K}$)

t_{3rd} : Time to initiation of tertiary creep (hr)

Fig. 13. Larson-Miller plots of stress vs. time to initiation of tertiary creep data for Hastelloy X

stress vs. secondary creep rate, stress vs. time to initiation of secondary creep, and stress vs. time to initiation of tertiary creep for Hastelloy X obtained in the present tests are shown in Figs. 10 to 13 respectively. A numeral "15" was used as the parameter constant, because it was reported that it gave good fits for a heat resistant alloy like Hastelloy X.³⁾ It is seen that a relative good correlation exists between stress and the parameter on these figures.

IV. A Method for Arranging the Data Required for the Elevated Temperature Structural Design from Creep Test Data

Design stress intensities of materials used at elevated temperatures cannot be determined indiscriminately but must be determined for every design conditions. Main design stress intensities are classified as shown in Table 2.⁴⁾ It is noticed that creep strength is taken into account only in determining stress intensities S_0 and S_t .

Figure 14 shows a method for arranging the data required for the elevated temperature structural design from creep test data. In creep data required for determining S_0 and S_t , the stress vs. time to rupture,

Table 2. Classification of design stress intensities

Stress intensity	Definition	Creep data required
S_o	1) The mean stress to cause creep rate of $10^{-5}\%$ /hr 2) 2/3 of the mean stress to cause rupture at 10^5 hr 3) 4/5 of the minimum stress to cause rupture at 10^5 hr } Minimum value	1) Stress to secondary creep rate curves 2) Stress to rupture curves
S_m	The lowest stress intensity value at a given temperature among the time-independent strength quantities	
S_t	1) 2/3 of the minimum stress to cause rupture 2) The minimum stress required to obtain a total strain of 1% 3) 4/5 of the minimum stress to cause initiation of tertiary creep } Minimum value	1) Stress to rupture curves 2) Isochronous stress-strain curves 3) Stress to initiation of tertiary creep curves
S_{mt}	The lower of two stress intensity values, S_m and S_t	
S_y	The minimum expected uniaxial yield stress of a material at a given temperature and for a strain rate of 0.005/min

Fig. 14. A method for arranging necessary design data for comparatively short-term creep data

stress *vs.* secondary creep rate, and stress *vs.* time to initiation of tertiary creep can be arranged through the Larson-Miller parameter. Although there still remain some problems in regard to an accuracy of extrapolation of long-term data through the Larson-Miller parameter, the data at arbitrary temperature can be estimated from short-term data by using this parameter.

In the isochronous stress-strain curve, the usual form of the curve plots stress on the ordinate and total strain on the abscissa for constant temperature. Several methods by which the isochronous stress-strain curves are obtained from creep and rupture data have been proposed.⁵⁻⁸⁾ The curve for long time can be constructed, for example, by using constitutive equations of creep made from short-term creep data.

1. Constitutive Equation of Creep

The following equation of time law which represents creep behavior except tertiary creep stage was proposed.^{1,2)}

$$\varepsilon = \varepsilon_0 + \beta_0 \sigma^m t^n + K_0 \sigma^{m'} t \quad \text{.....(10)}$$

In this study, Eq. (10) was divided into the primary and secondary creep stages:

Primary creep stage:

$$\varepsilon = \varepsilon_0 + \beta_0 \sigma^m t^n \quad \text{.....(11)}$$

Secondary creep stage:

$$\varepsilon = \varepsilon_0 + \beta_0 \sigma^m t_1^n + \dot{\varepsilon}_{\min}(t - t_1) \quad \text{.....(12)}$$

where t_1 is time to initiation of secondary creep.

Instantaneous strain, ε_0 , was negligible in the present tests, and it was assumed that $\varepsilon_0 = 0$. As mentioned in Section III. 3, constant n can be obtained from a creep rate curve. Further, constants m and β_0 can be obtained from the curves of stress *vs.* primary creep rate. The constitutive equation of creep of HAEN at 1 000°C obtained thus is shown as follows.

Primary creep stage:

$$\varepsilon = 3.04 \times 10^{-2} \sigma^{2.83} t^{0.41} \quad \text{.....(13)}$$

Secondary creep stage:

$$\varepsilon = 3.04 \times 10^{-2} \sigma^{2.83} t_1^{0.41} + \dot{\varepsilon}_{\min}(t - t_1) \quad \text{.....(14)}$$

where t_1 and $\dot{\varepsilon}_{\min}$ at an arbitrary stress can be obtained from Figs. 12 and 11.

Figure 15 shows the comparison of the predicted creep curve with the experimental one. Both the curves agree well.

2. Construction of Isochronous Stress-Strain Curve from Constitutive Equation of Creep

Figures 16 to 18 show the isochronous stress-strain curves at 800°, 900° and 1 000°C respectively for HAEN derived from the constitutive equation of

Fig. 15. Comparison of predicted creep curves with experimental creep curves

Fig. 16. Isochronous stress-strain curves at 800°C for Hastelloy X (HAEN) derived from predicted creep curves

creep. In these figures experimental data were plotted in order to confirm the reliability of the curve. The reliability of the curves for long time cannot be discussed, because there is no experimental data beyond 3 000 hr. Within a range under 1 000 hr, however, a fairly good approximation between the predicted data and the experimental data was obtained. Good approximations like this within the range under 1 000 hr were obtained not only for HAEN but also for the other heats. There were, however, remarkable differences of the isochronous stress-strain curves among the three heats. Therefore, in order to construct the isochronous stress-strain curves for Hastelloy X, it is necessary to accumulate the creep data for various heats of Hastelloy X and to analyze the data statistically.

V. Conclusions

Creep and stress rupture tests on three heats of Hastelloy X differing in the manufacturing process were carried out at 800°, 900° and 1 000°C. The creep behavior obtained was analyzed, and a method for predicting design data from the experimental results was discussed. The results obtained are as follows.

(1) It was difficult to separate the primary, the secondary and the tertiary creep stages in the creep

Fig. 17. Isochronous stress-strain curves at 900°C for Hastelloy X (HAEN) derived from predicted creep curves

Fig. 18. Isochronous stress-strain curves at 1 000°C for Hastelloy X (HAEN) derived from predicted creep curves

curve of Hastelloy X of the present tests. It was found, however, that those stages were made distinguishable by plotting creep rates *vs.* time in double-logarithmic coordinates. From these curves, the primary and the secondary creep rates and the times to initiation of the secondary and the tertiary creeps were derived.

(2) All the creep data, except the isochronous stress-strain curve, required for the design such as stress *vs.* rupture time, stress *vs.* secondary creep rate and stress *vs.* time to initiation of tertiary creep could be arranged through the Larson-Miller parameter. On the other hand, the isochronous stress-strain curve could be easily calculated by analyzing creep curves. The constitutive equations of creep for a heat of Hastelloy X proposed in this paper and the isochronous stress-strain curves derived from these equations nearly coincided with the experimental data.

REFERENCES

- 1) T. Nishihara, S. Taira, K. Tanaka and M. Ohnami: *Trans. Japan Soc. Mechan. Eng.*, **24** (1958), 424.
- 2) M. Ohnami: *J. JSTM*, **8** (1959), 199.
- 3) The 122nd and 123rd Comm. of Japan Society for the

- Promotion of Science: Report on Heat-resistant Alloys for VHTR, No. 2 (1974), 112.
- 4) T. Kodaira, T. Uga and M. Suzuki: Japan Atomic Energy Research Institute (JAERI)-M 6213, (1975), 12.
 - 5) D. I. Robert and S. A. Sterling: "A Parametric Method for the Development of Isochronous Stress-Strain Curves," Preprint for the Winter Annual Meeting of ASME, (1972), 1.
 - 6) L. D. Blackburn: "Isochronous Stress-Strain Curves for Austenitic Stainless Steels," Preprint for the Winter Annual Meeting of ASME, (1972), 15.
 - 7) J. B. Conway: "Parametric Considerations Applied to Isochronous Stress-Strain Plots," Preprint for the Winter Annual Meeting of ASME, (1972), 55.
 - 8) R. M. Goldhoff: "Method for Constructing Isochronous Creep Curves," Preprint for the Winter Annual Meeting of ASME, (1972), 67.