6.11 COMPARISON OF CREEP BEHAVIOR UNDER VARYING LOAD/TEMPERATURE CONDITIONS BETWEEN HASTELLOY XR ALLOYS WITH DIFFERENT BORON CONTENT LEVELS

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ABSTRACT

In the course of Japanese research and development of high-temperature gas-cooled reactors (HTGRs), the High-Temperature Engineering Test Reactor (HTTR) was planned to be constructed as the first reactor, and it is currently under construction at Oarai Research Establishment of the Japan Atomic Energy Research Institute. A nickel-base heat-resistant alloy, Hastelloy XR was developed as the structural material for high-temperature components of the HTTR. Creep data of Hastelloy XR have been accumulated both in simulated HTGR helium gas and in air environments for the design and safety evaluation of the high-temperature components of the HTTR. The research on the creep behavior of Hastelloy XR has revealed that the creep properties of the alloy depend strongly on the boron content level. The boron content level is determined to be equal or less than 100 mass ppm in the specification of Hastelloy XR. Even within the range, Hastelloy XR shows the very different creep rupture strength according to the amount of boron content.

In the design of the high-temperature components, it is often required to predict the creep rupture life under conditions in which the stress and/or temperature may vary by using the data obtained with the constant load and temperature creep rupture tests. Some conventional

creep damage rules have been proposed to meet the above-mentioned requirement. The applicability of the proposed creep damage rules seems to depend strongly on materials. Currently only limited data are available on the behavior of Hastelloy XR under varying stress and/or temperature creep conditions.

Hence a series of constant load and temperature creep rupture tests as well as varying load and temperature creep rupture tests was carried out on two kinds of Hastelloy XR alloys whose boron content levels are different, i.e., below 10 and 60 mass ppm, in order to examine the behavior of the alloy under varying load and temperature conditions.

The life fraction rule completely fails in the prediction of the creep rupture life of Hastelloy XR with 60 mass ppm boron under varying load and temperature conditions though the rule shows good applicability for Hastelloy XR with below 10 mass ppm boron. The change of boron content level of the material during the tests is the most probable source of impairing the applicability of the life fraction rule to Hastelloy XR whose boron content level is 60 mass ppm. The modified life fraction rule has been proposed based on the dependence of the creep rupture strength on the boron content level of the alloy. The modified rule successfully predicts the creep rupture life under the two stage creep test conditions from 1000°C to 900°C. The trend observed in the two stage creep tests from 900°C to 1000°C can be qualitatively explained by the mechanism that the oxide film which is formed during the prior exposure to 900°C plays the role of the protective barrier against the boron dissipation into the environment.

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ABSTRACT

In the design of the high-temperature components, it is often required to predict the creep rupture life under the conditions in which the stress and/or temperature may vary by using the data obtained with the constant load and temperature creep rupture tests. Some conventional creep damage rules have been proposed to meet the above-mentioned requirement. The applicability of the proposed creep damage rules seems to depend strongly on materials. Currently only limited data are available on the behavior of Hastelloy XR, which is a developed alloy as the structural material for high-temperature components of the High-Temperature Engineering Test Reactor (HTTR), under varying stress and/or temperature creep conditions.

Hence a series of constant load and temperature creep rupture tests as well as varying load and temperature creep rupture tests was carried out on two kinds of Hastelloy XR alloys whose boron content levels are different, *i.e.*, below 10 and 60 mass ppm, in order to examine the behavior of the alloy under varying load and temperature conditions.

The life fraction rule completely fails in the prediction of the creep rupture life of Hastelloy XR with 60 mass ppm boron under varying load and temperature conditions though the rule shows good applicability for Hastelloy XR with below 10 mass ppm boron. The change of boron content level of the material during the tests is the most probable source of impairing the applicability of the life fraction rule to Hastelloy XR whose boron content level is 60 mass ppm. The modified life fraction rule has been proposed based on the dependence of the creep rupture strength on the boron content level of the alloy. The modified rule successfully predicts the creep rupture life under the two stage creep test conditions from 1000 to 900°C. The trend observed in the two stage creep tests from 900 to 1000°C can be qualitatively explained by the mechanism that the oxide film which is formed during the prior exposure to 900°C plays the role of the protective barrier against the boron dissipation into the environment.

1. Introduction

In the course of Japanese research and development of high-temperature gas-cooled reactors (HTGRs), the High-Temperature Engineering Test Reactor (HTTR) was planned to be constructed as the first reactor, and it is currently under construction at Oarai Research Establishment of the Japan Atomic Energy Research Institute. A nickel-base heat-resistant alloy, Hastelloy XR was developed as the structural material for the HTTR [1-3]. Hastelloy XR has a common basal composition for the major constituents with Hastelloy X (*i.e.*, nominally Ni - 22 mass% Cr - 18 mass% Fe - 9 mass% Mo), while minor elements such as Mn and Si are adjusted in the optimum ranges and Al, Ti and Co are eliminated to the lowest possible levels [1,3]. As the result of the above-mentioned modification, Hastelloy XR is known to have the substantially improved corrosion resistance in the simulated HTGR helium environment and the improved applicability to the HTTR relative to Hastelloy X [1-3].

Creep data for Hastelloy XR have been accumulated both in simulated HTGR helium and air environments for the design and safety evaluation of the high-temperature components of the HTTR. The research on the creep behavior of Hastelloy XR has revealed that the creep properties of the alloy depend strongly on the boron content level [4,5]. The boron content level is determined to be equal or less than 100 mass ppm in the specification of Hastelloy XR [1]. Even within the range, Hastelloy XR shows the very different creep rupture strength according to the amount of boron content as indicated in Fig. 1 [4].

In the design of the high-temperature components, it is often required to predict the creep rupture life under the conditions in which the stress and/or temperature may vary by using the data obtained with the constant load and temperature creep rupture tests. Some conventional creep damage rules have been proposed to meet the above-mentioned requirement. The applicability of the proposed creep damage rules seems to depend strongly on materials. Currently only limited data are available on the behavior of Hastelloy XR under varying stress and/or temperature creep conditions.

Hence a series of constant load and temperature creep rupture tests as well as varying load and temperature creep rupture tests was carried out on two kinds of Hastelloy XR alloys whose boron content levels are different, *i.e.*, below 10 and 60 mass ppm, in order to examine the behavior of the alloys under varying load and temperature conditions.

2. Experimental Procedures

2.1 Materials

The materials tested in this study are two kinds of commercially manufactured Hastelloy XR alloys whose boron content levels are different. The chemical compositions and the tensile properties of the materials are listed in Tables 1, 2 and 3. As shown in Table 1, the boron content levels of them are 1 to 2 mass ppm for Heat 1 and 60 mass ppm for Heat 2. The materials were solution annealed at 1190°C for 1 h followed by water quenching.

2.2 Creep rupture tests

Creep rupture tests were accomplished by using specimens with 6 mm in diameter and 30 mm in gauge length. The tests were performed with lever-type creep testers. Some tests were carried out in simulated HTGR helium gas environments, and others in air. The test section used for the tests in simulated HTGR helium gas environments was encased in a vacuum tight chamber connected to a circulating helium loop system. A series of constant load and temperature creep rupture tests as well as varying load and/or temperature creep rupture tests was conducted at 850, 900, 950 and 1000°C. Two types of simulated HTGR helium gas were employed, and the impurity contents in the gas are indicated in Table 4. The characterizations of these environments have been reported elsewhere [6], and they are essentially equivalent from the viewpoints of the chemical reactions between the material and the environment [6]. Test temperatures were chosen considering the outlet coolant temperatures of the HTTR which were 850°C at the rated operation and 950°C at the high temperature test operation. Stress levels were chosen with intention of the maximum rupture life being within 104 h.

3. Results and discussion

3.1 Constant load and temperature creep rupture tests

Figure 2 shows the relation between the applied stress, which is a nominal stress given by the load divided by the initial cross-sectional area, and the time to rupture obtained with the constant load and temperature creep rupture tests on Heat 1 whose boron content level is 1 to 2 mass ppm. The relation can be expressed as

$$t_R = 1.283 \times 10^{12} \sigma^{-5.458} \text{ at } 850°C, \quad (1)$$

$$t_R = 2.944 \times 10^{9} \sigma^{-4.272} \text{ at } 900°C, \quad (2)$$

$$t_R = 1.550 \times 10^8 \sigma^{-3.891} \text{ at } 950°C \tag{3}$$

and

$$t_R = 1.013 \times 10^7 \sigma^{-3.466} \text{ at } 1000°C, \tag{4}$$

where t_R is the time to rupture in hour and σ is the applied stress in MPa.

Figure 3 shows the relation between the applied stress, which is a nominal stress given by the load divided by the initial cross-sectional area, and the time to rupture obtained with the constant load and temperature creep rupture tests on Heat 2 whose boron content level is 60 mass ppm. In the figure, not only the data obtained in the present study but also those obtained for the same heat material in another work [7] are plotted. There is no significant difference in the creep rupture life among three test environments within the range tested. The relation between the applied stress and the time to rupture can be expressed as follows;

$$t_R = 3.849 \times 10^{13} \sigma^{-6.390} \text{ at } 900°C \tag{5}$$

and

$$t_R = 1.225 \times 10^8 \sigma^{-3.964} \text{ at } 1000°C, \tag{6}$$

where t_R is the time to rupture in hour and σ is the applied stress in MPa.

3.2 Creep damage rules

In the design of the high-temperature components, it is usually required to predict the creep rupture life under the conditions where the stress and/or temperature may vary from the data obtained with the constant load and temperature creep rupture tests. Some conventional creep damage rules have been proposed to meet such a requirement [8-13].

The life fraction rule, which has been widely utilized in the engineering design of high-temperature components, was proposed by Robinson [8,9]. According to the rule, creep rupture is predicted to occur when the summation of the life fractions is equal to unity, *i.e.*, the rule is expressed as

$$\sum_i \frac{\Delta t_i}{t_{Ri}} = 1, \tag{7}$$

where Δt_i is the period of time spent under a particular stress and temperature, and t_{Ri} is the rupture time corresponding to this stress and temperature. This rule has supported by several investigators

[14-17], while other investigators reported several cases where the prediction of this rule was unsatisfactory [10-13,18-20].

An analogous rule, which is known as the strain fraction rule, was proposed by Lieberman [10]. According to the rule, creep rupture is predicted to occur when the summation of the strain fractions is equal to unity, *i.e.* , the rule is expressed as

$$\sum_i \frac{\Delta\varepsilon_i}{\varepsilon_{Ri}} = 1, \tag{8}$$

where $\Delta\varepsilon_i$ is the strain under a given stress and temperature, and ε_{Ri} the strain at rupture under the same stress and temperature.

The mixed criterion of the two above-mentioned rules was proposed by Voorhees & Freeman [11,12]. In the criterion, the condition where creep rupture is predicted to occur is given as follows;

$$\sum_i \sqrt{\frac{\Delta t_i}{t_{Ri}} \cdot \frac{\Delta\varepsilon_i}{\varepsilon_{Ri}}} = 1. \tag{9}$$

Furthermore an attempt of modifying the mixed criterion was made by Abo El Ata & Finnie [13]. In the modified criterion, the condition where creep rupture is prediction to occur is given as follows;

$$K\sum_i \frac{\Delta t_i}{t_{Ri}} + (1-K)\sum_i \frac{\Delta\varepsilon_i}{\varepsilon_{Ri}} = 1, \tag{10}$$

where K is the material constant between zero and one which indicates the ability of the material to resist cracking during creep.

In the design of the high-temperature components of the HTTR, the life fraction rule was applied among the above-mentioned conventional creep damage rules from the viewpoints of actual experience and simplicity [1]. Applicability of the life fraction rule, therefore, was examined to the data obtained in the present study.

3.3 Results of application of life fraction rule

Figure 4 shows the results of application of the life fraction rule to the varying stress and/or temperature test results on Heat 1. In the figure, the life fraction $\Delta t_i / t_R$ was obtained using the calculated values with Eqs. (1) to (4) as t_R. The summation of the life fractions ranges from 0.69 to 1.36, the average is 0.96, and the standard deviation is 0.19. These values suggest that the life fraction rule is applicable in engineering design of high-temperature components made of Hastelloy XR whose boron content level is below 10 mass ppm.

Figures 5 and 6 show the results of application of the life fraction rule to the varying stress and temperature test results on Heat 2. In these figures, the life fraction $\Delta t_i / t_R$ was obtained using the calculated values with Eqs. (5) and (6) as t_R. As can be seen in these figures, the life fraction rule completely fails in the prediction of the creep rupture life under varying load and temperature conditions in contrast with the result for Heat 1. The data tend to be located in the higher portion than the line which shows the summation of the life fraction is equal to unity in Fig. 5, *i.e.*, in the tests from 900 to 1000°C. On the contrary, all the data are located in the lower portion than the line which shows the summation of the life fractions is equal to unity in Fig. 6, *i.e.*, the tests from 1000 to 900°C.

3.4 Possible sources of changes in creep strength

In general, the life fraction rule shows good applicability to the material whose creep strength is not strongly affected by the change of the chemical composition and/or the microstructure of the material which occurs during exposure to the high-temperature environment. In the present study, the followings may be taken into consideration as the change of the chemical composition and/or the microstructure which may occur during exposure to the high-temperature environment, and may affect the creep strength;

(1) change of carbon content,
(2) change of chromium content,
(3) precipitation of carbides, and
(4) recrystallization, for both materials, and
(5) change of boron content, for Heat 2.

It is known that the creep strength of Hastelloy XR strongly depends on the carbon content level [21,22], and that carburization or decarburization may occur in the helium gas environment which contains specific levels of impurities for the alloy [21,22]. However in the environments employed in the present study, Hastelloy XR indicates protective corrosion behavior, and only mild carburization, which does not significantly affect the creep strength of the alloy [21,22], occurs [6].

It is also known that the chromium depleted zone is formed near the surface region of the material by exposure to the high-temperature simulated HTGR helium gas environments [3]. Such a phenomenon might cause the creep strength reduction. The depth of the chromium depleted zone, however, is estimated below 200 μm even in the condition where Δt_1 is the longest at 1000°C [23]. The value is small relative to the diameter of the creep specimen, *i.e.*, 6 mm, employed in the present study. The phenomenon, therefore, does not affect the creep strength of Hastelloy XR significantly [24].

During exposure to the high-temperature test environment, carbides precipitate and may grow in Hastelloy XR. Precipitation of carbides is considered to contribute to the creep strength of the material, and there may be the most preferable amount and size of precipitates for the contribution. The amount and the size of precipitates are considered to depend on the exposed temperature more strongly than on the applied stress level. This may cause the tendency that the applicability of the life fraction rule under varying both stress and temperature conditions is slightly inferior to that under varying stress and constant temperature conditions as shown in Fig. 4.

Recrystallization might occur in Hastelloy XR crept at 1000°C [25]. Such a phenomenon might cause the creep strength reduction. Recrystallization occurs more easily in the material whose boron content level is below 10 mass ppm such as Heat 1 than the material with 50 to 60 mass ppm boron such as Heat 2 [26]. If this mechanism is dominant, the life fraction in the second stage becomes lower for Heat 1 under varying stress and temperature conditions from 1000 to 900°C, especially in the conditions where Δt_1 is long. Such a trend, however, cannot be observed in Fig. 4.

As already mentioned in section 1, the creep strength of Hastelloy XR depends strongly on the boron content level (see Fig. 1). If the amount of boron content decreases during exposure to the high-temperature environment, the creep strength of the alloy will reduce.

Among the above-mentioned five items, the items (1) to (4) are common to both of Heats 1 and 2, while the item (5) is specific to Heat 2. The item (5), therefore, is the most possible as the factor which caused the difference in the applicability of the life fraction rule between Heats 1 and 2 whose boron content levels are different.

3.5 Results of boron analyses

In order to examine the changes in the amount of boron content, boron analyses were made for the crept specimens of Heat 2. In some cases the specimens for boron analyses were separated into two portions, *i.e.*, the core and the surface portions as shown in Fig. 7, and in other cases the specimens were used for boron analyses in all. The specimens for boron analyses were selected from the crept ones indicated in Figs. 3, 5 and 6, and some specimens for boron analyses were newly prepared by conducting interruption creep tests under constant load and temperature conditions.

Figures 8 and 9 show the results of boron analyses as a function of the exposure time to the high-temperature environments at 900 and 1000°C, respectively. In the figures only one stage test results are shown, and no results under varying load and temperature conditions are indicated. It is clearly recognized that the amount of boron content reduces with increasing the exposure time at 1000°C in Fig. 9. Even at 900°C such a tendency is observed in Fig. 8. The boron content reduction rate at 900°C, however, is much lower than that at 1000°C. The amount of boron content at the surface portion tends to be smaller than that at the core portion, *i.e.*, open symbols are generally located in the lower portion than solid ones in Figs. 8 and 9. The fact suggests that boron in the material dissipates from the surface as the result of the reaction with the high-temperature environments and that boron is supplied by the diffusion flow from the core portion to the surface.

Figure 9 suggests that the amount of boron content of the material crept at 1000°C in the first stage is lower than the original level at the point when the test conditions were changed from 1000 to 900°C. This mechanism may play the major role in impairing the reliability of the life fraction rule in Fig. 6, in which the creep lives in the second stage are extremely short.

3.6 Modification of life fraction rule

It is preferable to apply the evaluation method which takes account of the change of the chemical composition and/or the microstructure of the material which occurs during exposure to the high-temperature environment for the precise prediction of the creep rupture life under varying load and temperature conditions [19,20]. Since the above-mentioned mechanism seems to play the major role in impairing the reliability of the life fraction rule for Heat 2, the modification of the rule may be effective based on the dependence of the creep rupture strength on the boron content level of the alloy. In order to simplify the discussion, the followings are assumed:

(1) The boron content reduction at 900°C is negligible.

(2) There is no difference in the creep rupture life among three environments employed in the present study.

(3) The bulk boron content level is a mean value of the boron analyzed results of the core and the surface portions.

(4) The creep rupture life of the material whose boron content level is below 60 mass ppm becomes shorter along the line A linearly in a logarithm scale in Fig. 10.

By adding the results of boron analyses for the specimens crept under varying load and temperature conditions to Fig. 9 based on the assumption (1), Fig. 11 was obtained. According to the assumption (1), the amount of boron content after creep rupture tests under the conditions from 1000 to 900°C can be regarded as the boron content level of the material at the point when the test conditions were changed from 1000 to 900°C. Consequently the creep rupture life of the material whose boron content level is equal to that of the material at the point when the test conditions were changed from 1000 to 900°C can be estimated based on the assumptions (2), (3) and (4).

Figure 12 shows the result of the application of the above-mentioned method. Comparison of Fig. 12 with Fig. 6 clearly shows that the creep rupture life under varying load and temperature conditions is predicted more successfully by the modified life fraction rule based on the dependence of the creep rupture strength on the boron content level than by the fraction rule.

By the way, the tendency is observed that the boron content reduction rate under the condition from 900 to 1000°C is low in Fig. 11. The tendency suggests that the prior exposure to 900°C could delay the phenomenon of boron dissipation during the following exposure to 1000°C. The oxide film which is formed on the surface of the specimen during the exposure to 900°C might play the role of the protective barrier against the boron dissipation into the environment. Since Eq. (6) expresses the relation between the applied stress and the time to rupture in the case where the amount of boron content of the material reduces gradually, the creep rupture life would be longer in the case where the boron content reduction rate is low than that calculated with Eq. (6). This mechanism can qualitatively explain the trend that the data are located in the higher portion than the line which shows the summation of the life fractions is equal to unity in Fig. 5, *i.e.*, in the tests from 900 to 1000°C.

4. Conclusions

A series of constant load and temperature creep rupture tests as well as varying load and temperature creep rupture tests was carried out on two kinds of Hastelloy XR alloys whose boron content levels are below 10 and 60 mass ppm at 850 to 1000°C in order to examine the behavior of the alloys under varying load and temperature conditions. Based on the results obtained the following conclusions are drawn:

(1) The life fraction rule shows good applicability for Hastelloy XR whose boron content level is below 10 mass ppm.

(2) The life fraction rule completely fails in the prediction of the creep rupture life under varying load and temperature conditions for Hastelloy XR whose boron content level is 60 mass ppm.

(3) The change of boron content level of the material during the tests is the most probable source

of impairing the reliability of the life fraction rule for the alloy with 60 mass ppm boron.

(4) The modified life fraction rule has been proposed based on the dependence of the creep rupture strength on the boron content level of the alloy. The modified rule successfully predicts the creep rupture life of the alloy with 60 mass ppm boron under the test condition from 1000 to 900°C.

(5) The trend observed in the tests from 900 to 1000°C for the alloy with 60 mass ppm boron can be qualitatively explained by the mechanism that the oxide film which is formed during the prior exposure to 900°C plays the role of the protective barrier against the boron dissipation into the environment.

Acknowledgement

The authors are grateful to Dr. H. Shiraishi of the National Research Institute for Metals and Dr. T. Kondo of Tohoku University for their advice and encouragement.

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Table 1 Chemical compositions of the materials tested (mass%).

		C	Si	Mn	P	S	Cr	Co	Mo	W	Fe	B	Al	Ti	N	Ni
Heat 1	T	0.07	0.32	0.96	<0.001	<0.001	22.00	0.02	9.11	0.49	18.59	0.0002	0.01	0.01	0.007	Bal.
	B	0.07	0.33	0.93	<0.001	<0.001	21.96	0.03	9.11	0.49	18.62	0.0001	0.02	<0.01	0.006	Bal.
Heat 2		0.07	0.33	0.88	<0.001	0.001	21.99	0.06	8.73	0.63	17.80	0.006	0.03	0.01	0.006	Bal.

T : Top side of the ingot, B : Bottom side of the ingot

Table 2 Tensile properties of Heat 1 at room temperature and at temperatures where creep rupture tests were conducted.

Test temp. (℃)	Strain rate (%/s)	0.2% Proof stress (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)	Reduction of area (%)
RT	5×10^{-3} (first stage) 1.25×10^{-1} (second stage)	301 - 323	688 - 697	57.1 - 62.8	62.8 - 64.6
Strain rate was changed at a strain of 1.5%.			Frequency was four.		
850	5×10^{-3}	188	203	116.3	75.2
	1.25×10^{-1}	155	250	108.9	80.2
	2.5×10^{-1}	147	274	84.6	74.3
900	5×10^{-3}	153	172	126.2	69.2
	1.25×10^{-1}	149	195	101.1	82.5
	2.5×10^{-1}	146	217	101.5	78.5
950	5×10^{-3}	117	137	94.6	67.2
	1.25×10^{-1}	136	172	122.3	83.8
	2.5×10^{-1}	143	171	101.7	80.7
1000	5×10^{-3}	81	103	86.7	64.1
	1.25×10^{-1}	123	136	132.7	84.0
	2.5×10^{-1}	129	145	100.4	79.6

Table 3 Tensile properties of Heat 2 at room temperature and at temperatures where creep rupture tests were conducted.

Test temp. (℃)	Strain rate (%/s)	0.2% Proof stress (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)	Reduction of area (%)
RT	5×10^{-3} (first stage) 1.25×10^{-1} (second stage)	289	685	56.9	60.9
Strain rate was changed at a strain of 3%.					
900	5×10^{-3}	127	133	109.7	78.1
	1.25×10^{-1}	160	161	91.3	81.4
	2.5×10^{-1}	175	204	120.7	89.8
1000	5×10^{-3}	72	75	93.0	66.6
	1.25×10^{-1}	89	109	119.3	79.3
	2.5×10^{-1}	116	145	104.2	82.1

Table 4 Impurity levels in simulated HTGR helium gas environments (vol ppm).

	H_2	H_2O	CO	CO_2	CH_4
He-1	200	1	100	2	5
He-2	300	3	100	1	15

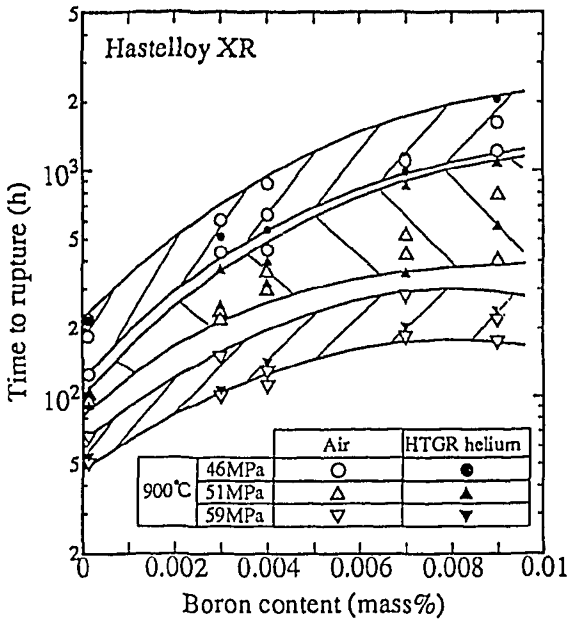

Fig. 1 Effect of the boron content level on the creep rupture life of Hastelloy XR [4].

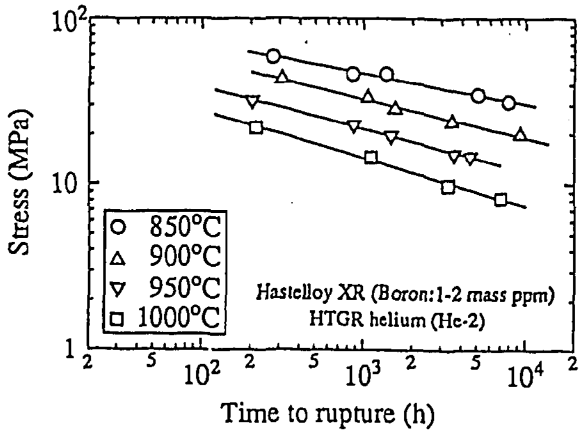

Fig. 2 Relation between applied stress and time to rupture obtained with constant load and temperature creep rupture tests for Hastelloy XR with 1 to 2 mass ppm boron.

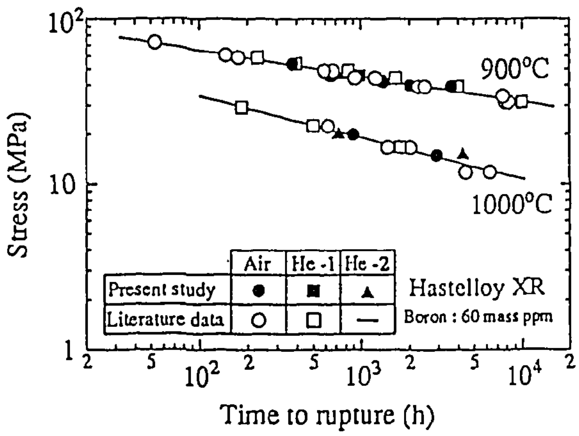

Fig. 3 Relation between applied stress and time to rupture obtained with constant load and temperature creep rupture tests for Hastelloy XR with 60 mass ppm boron. The figure includes both of the data obtained in the present study and in another work [7] for the same heat material.

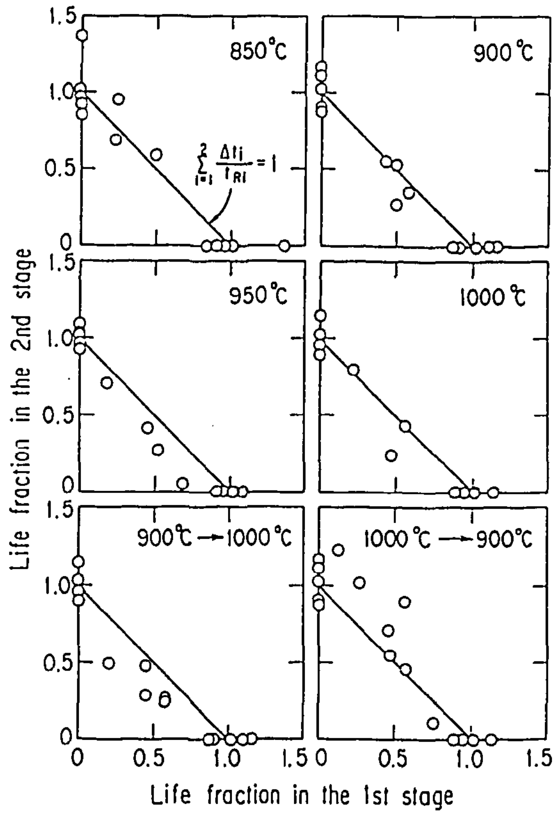

Fig. 4 Result of application of the life fraction rule to the varying stress and/or temperature test results for Hastelloy XR with 1 to 2 mass ppm boron.

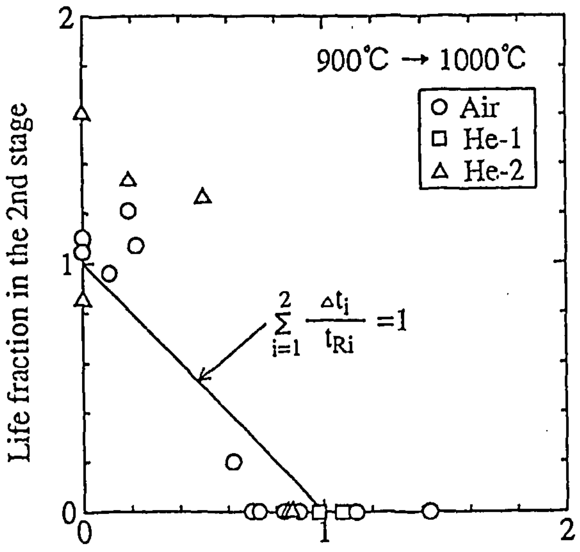

Fig. 5 Result of application of the life fraction rule to the test results under the conditions from 900 to 1000°C for Hastelloy XR with 60 mass ppm boron.

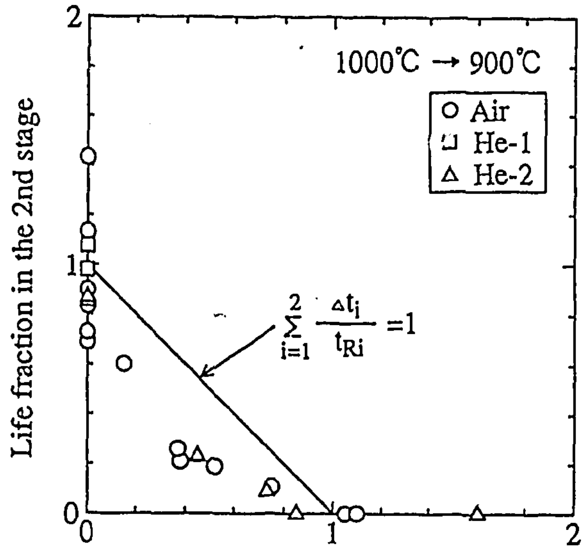

Fig. 6 Result of application of the life fraction rule to the test results under the conditions from 1000 to 900°C for Hastelloy XR with 60 mass ppm boron.

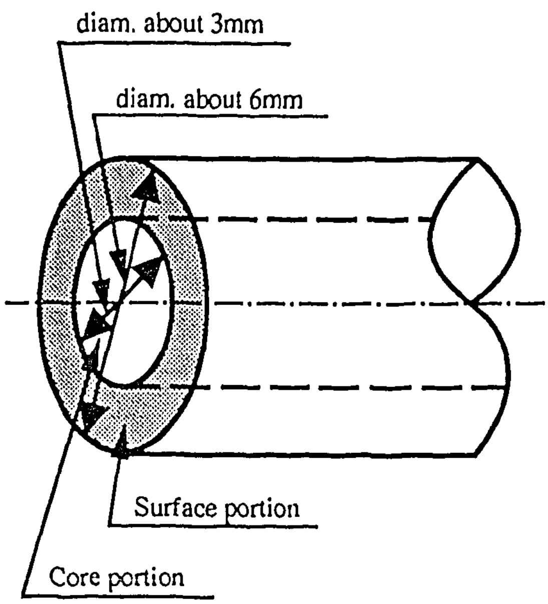

Fig. 7 Schematic illustration of the sampling method of specimens for boron analyses.

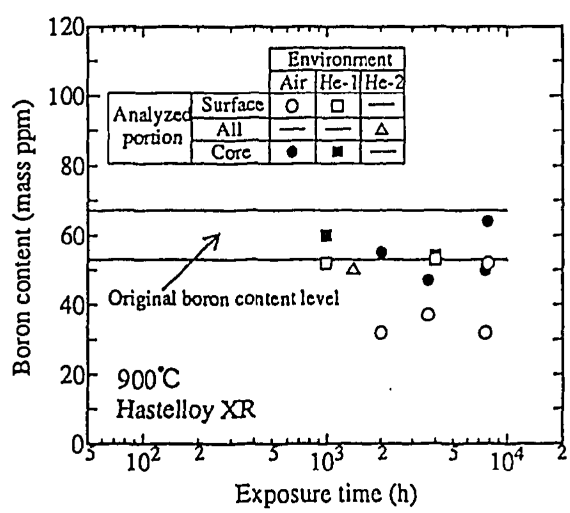

Fig. 8 Results of boron analyses as a function of the exposure time to the high-temperature environments at 900°C. The figure does not include the results under varying load and temperature conditions.

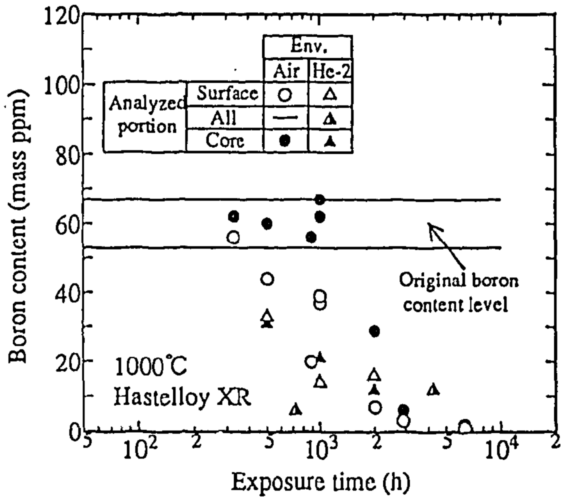

Fig. 9 Results of boron analyses as a function of the exposure time to the high-temperature environments at 1000°C. The figure does not include the results under varying load and temperature conditions.

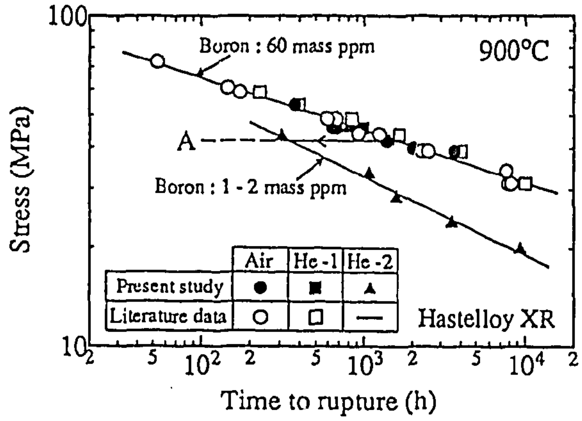

Fig. 10 Relation between applied stress and time to rupture obtained with constant load and temperature creep rupture tests for Hastelloy XR whose boron content levels are different. The figure includes the data obtained in another work [7] for the same heat material.

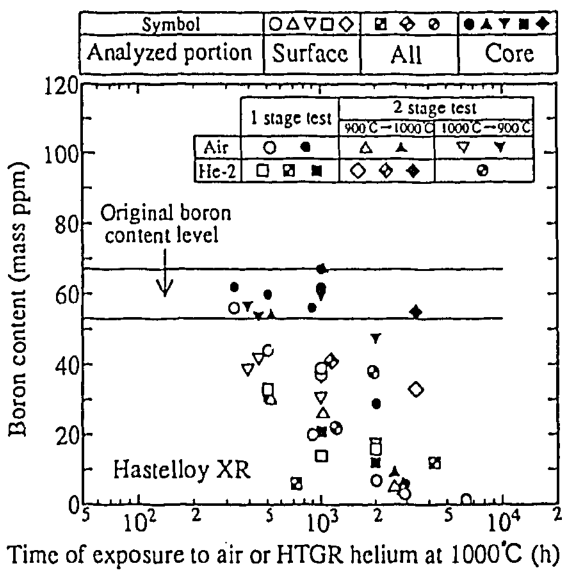

Fig. 11 Results of boron analyses as a function of the exposure time to high-temperature environments at 1000°C. The figure includes the results under varying load and temperature conditions.

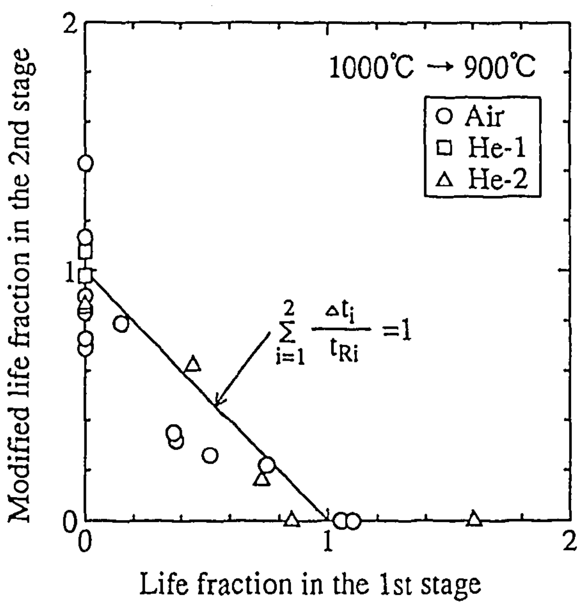

Fig. 12 Result of application of the modified life fraction rule to the test results under the conditions from 1000 to 900°C for Hastelloy XR with 60 mass ppm boron.