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Study on creep-fatigue life prediction methods for low-carbon nitrogen-controlled 316 stainless steel (316FR)

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Abstract

Low-carbon, nitrogen-controlled 316 stainless steel called 316FR was developed and is regarded as a principal candidate for a main structural material of liquid metal-cooled fast breeder reactor plants in Japan. To develop a creep-fatigue evaluation method suitable for this steel, a number of uniaxial creep-fatigue tests have been conducted for three products of this steel. Long-term data up to about 35,000 h were obtained and applicability of failure life prediction methods was studied based upon their results. Cruciform shaped specimens were also tested under biaxial loading conditions to examine the effect of stress multiaxiality on failure life under creep-fatigue condition.

1. Introduction

In liquid metal-cooled fast reactor plants constructed in the past, austenitic stainless steels have been used as a main structural material because of their superior high-temperature strength and ductility compared to many ferritic steels. In Japan, type 316 stainless steel with low-carbon and controlled-nitrogen called 316FR (fast reactor) was developed (Nakazawa et al., 1988) and its use in future reactors is planned, instead of type 304 stainless steel used in a prototype reactor, Monju. The chemical composition of this steel is similar to that of 316L(N) steel used in European fast reactors, but carbon content is more severely restricted in 316FR.

This steel has considerably better creep strength than the conventional type 316 steel with higher carbon content, mainly by reducing the amount of precipitation of chromium-carbides along grain boundaries, which promote initiation of creep cavities. However, the main loading mode in fast reactor components is creep–fatigue interaction principally under deformation control rather than simple creep, because thermal stresses are dominant compared to primary stresses due to low operating pressure. Therefore, developing a method which can predict creep-fatigue life with a reasonable accuracy is quite important for sound operation of the plant for a design life as long as 40 years or more.

The authors have been conducting long-term creep and creep-fatigue tests for several products of this steel (Takahashi, 1995). Results of these tests and evaluation of life prediction methods based upon them have been partially presented already (Takahashi, 1998b, 1999). Superiority of the ductility exhaustion approach against time fraction approach was made clear. Afterwards, additional tests at lower strain range or longer hold time were started to evaluate the applicability to longer-term region. Some new data have been obtained from these tests and the observations obtained in the early stage were re-evaluated. In order to address the concerns about applicability of the life prediction method to multiaxial stress states, biaxial fatigue and creep-fatigue tests using cruciform specimens were additionally performed during this phase of the program. This paper presents the results of these investigations.

2. Uniaxial creep-fatigue tests

2.1. Tested materials

Three kinds of products of 316FR used in creep tests (Takahashi et al., 2008) were mainly tested in this study. Two of them, called plate A and plate B hereafter, were produced by hot-rolling and their thickness was 50 mm, which is compa-

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Table 1
Chemical composition (wt%) and grain size of tested materials

Material	C	Si	Mn	P	S	Ni	Cr	Mo	N	Grain size number
Plate A	0.009	0.57	0.86	0.025	0.005	11.25	16.85	2.06	0.0766	4.0
Plate B	0.008	0.54	0.84	0.027	0.004	11.16	16.83	2.10	0.0754	5.5
Plate C	0.009	0.55	0.84	0.024	0.007	11.25	17.00	2.11	0.0751	4.0
Forging	0.008	0.48	0.82	0.025	0.003	11.41	16.57	2.03	0.0935	1.1
Specification	<0.02	0.30–0.75	0.50–1.50	0.02–0.03	<0.01	10.5–12.5	16.0–18.0	2.05–2.55	0.06–0.11	–

rable to thickness of reactor vessels of liquid metal-cooled fast reactor plants. Solution heat treatment was given at 1050 °C for 30 min followed by water quenching. Additional heat treatment (1250 °C, 16 h) was applied to the plate B prior to rolling in order to reduce the possibility of carbide precipitation by homogenizing chromium distribution. The third test material was produced by forging, and its original thickness was 400 mm. Solution heat treatment was made by keeping at 1050 °C for 7 h followed by water quenching.

Chemical composition and average grain size number in ASTM standard of these products are shown in Table 1 with recommended ranges provided for this steel. There is no significant difference between chemical compositions of each product, whereas grain size differs considerably.

2.2. Test conditions and testing methods

It is known that introduction of hold time at high-temperature reduces the number of cycles to failure from pure-fatigue loading due to “creep damage” or other mechanisms such as oxidation. It was reported in the past studies (e.g., Brinkman, 1985) that holding at the tensile strain gives larger life reduction than compressive holding for austenitic stainless steels, and that was confirmed by several tests for the present material (Takahashi, 1998a,b). Based on these facts, a number of tensile strain-hold, trapezoidal-wave, creep-fatigue tests have been conducted mainly at 550 and 600 °C.

The geometry of the test specimens used in the tests is shown in Fig. 1. Diameter of the test section is 8 mm and gage length for strain control is 12 mm. Nineteen electro-mechanical fatigue testing machines equipped with an electric furnace were used. The temperature of the test section was indirectly controlled by thermo-couples plugged into the electric furnace. Strain rate during ramping period was fixed at 0.1%/s. Failure life was defined as the cycle when the tensile peak stress became smaller than 75% of its maximum value experienced during the test. To obtain the fatigue damage per cycle, pure-fatigue tests were also conducted at the same strain range and strain rate.

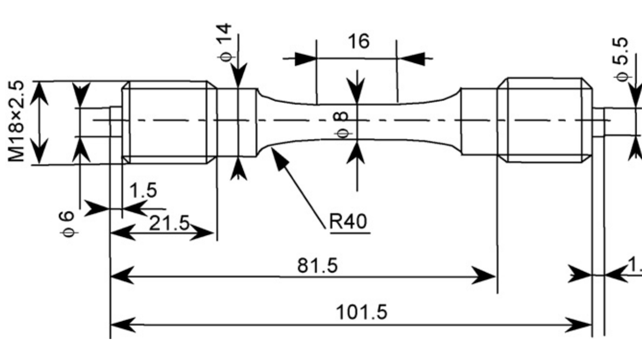

Fig. 1. Geometry of uniaxial creep-fatigue test specimen (dimensions in mm).

Table 2 shows the list of test conditions of pure-fatigue and creep-fatigue tests. A total of 38 creep-fatigue tests were conducted for different products and temperatures, changing strain range and hold time as shown in the table. The largest and smallest strain ranges were 1.0 and 0.3%, respectively, whereas the hold time was varied between 0.1 and 50 h.

2.3. Test results

Numbers of cycles to failure are summarized in Table 2. Three out of 38 tests have not been failed yet and are still continuing. Number of cycles to failure is plotted as a function of hold time in Fig. 2. The following observations can be made from the figure;

(i) At all conditions, the number of cycles to failure continuously decreased with the increase in hold time at a fixed strain range.
(ii) Ratio of life reduction became larger as the strain range became smaller (1/2 at 1.0% versus 1/70 at 0.35% by 1 h holding, for example).
(iii) Failure lives at 600 °C tended to be shorter than that at 550 °C, but the difference was much smaller than observed in the pure-creep tests. The difference of controlled parameters, i.e., stress versus strain, would be the reason for this.
(iv) At the same test conditions, plate A and the forging showed shorter life, whereas the life of plate B was longer than those. This trend coincides with that of ductility in the creep tests and a strong correlation between creep ductility and creep-fatigue life is suggested.

It may be appropriate to note that the test duration of many of the creep-fatigue tests conducted in the present study was much longer than that of the other works reported in the past for this steel (Wada et al., 1991; Ueta et al., 1995) and other types of 316 stainless steel (e.g., Wareing, 1981) because of smaller strain range or longer hold time, and these results constitute a good base for the evaluation of creep-fatigue evaluation methods.

3. Application of creep-fatigue life prediction methods

3.1. Outline of life prediction methods

3.1.1. Time fraction approach

In the current design codes for high-temperature components of fast reactors, time fraction approach was widely