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ELEVATED-TEMPERATURE MECHANICAL PROPERTIES OF AN ADVANCED TYPE 316 STAINLESS STEEL*

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ABSTRACT

Type 316FR stainless steel is a candidate material for the Japanese Demonstration Fast Breeder Reactor Plant to be built in Japan early in the next century. Like type 316L(N), it is a low-carbon grade of stainless steel with a more closely specified nitrogen content and chemistry optimized to enhance elevated-temperature performance. Early in 1994, under sponsorship of The Japan Atomic Power Company, work was initiated at Oak Ridge National Laboratory (ORNL) aimed at obtaining an elevated-temperature mechanical-properties database on a single heat of this material. The product form was 50-mm plate manufactured by the Nippon Steel Corporation. Data include results from long-term creep-rupture tests conducted at temperatures of 500 to 600°C with test times up to nearly 40,000 h, continuous-cycle strain-controlled fatigue test results over the same temperature range, limited creep-fatigue data at 550 and 600°C, and tensile test properties from room temperature to 650°C. The ORNL data were compared with data obtained from several different heats and product forms of this material obtained at Japanese laboratories. The data were also compared with results from predictive equations developed for this material and with data available for type 316 and type 316L(N) stainless steel.

INTRODUCTION

Type 316FR (Fast Reactor) is a candidate structural steel for use in the Japanese Demonstration Fast Breeder Reactor (DFBR) to be constructed early in the next century (Miura et al., 1992). It is a modified version of type 316 stainless steel with low carbon and restricted chemistry (Asada et al., 1992) as shown in Table 1, where its chemistry is compared with those of several similar versions of this steel. The Japan Atomic Power Company (JAPC), which has responsibility for conducting the design study for the DFBR, decided early in 1994 to sponsor work at Oak Ridge National Laboratory (ORNL) aimed at obtaining elevated-temperature mechanical properties on this material to supplement efforts in Japan. Work has continued since that time at ORNL and at the Idaho National Engineering and Environmental Laboratory (INEEL) aimed at generating tensile, creep, fatigue, and creep-fatigue data for this steel. It is the objective of this paper to present some of the mechanical-properties data generated to date and to compare the data with similar data generated by several laboratories in Japan. Comparisons are also made with data obtained from tests conducted on type 316 stainless steel in the United States and type 316L(N) in Europe.

MATERIAL AND TEST PROCEDURE

Type 316FR plate (50 mm thick) was furnished by Nippon Steel Corporation. The plate identified as No. 606149 (heat N99780) had been solution annealed at 1050°C for 0.5 h followed by water cooling. Chemical composition is given in Table 1. Metallographic examination indicated that the material had an average American Society for Testing and Materials (ASTM) grain size of 4 and that the microstructure was very clean, nearly free of any precipitates and stringers as viewed under an optical microscope. Specimen blanks were sectioned from the plate so that their loading axes would be parallel to the rolling direction and their centerlines would be 12.5 mm from the plate surface. Tensile and creep tests were conducted in accordance with ASTM specifications E 21 and E 139, respectively.

Strain-controlled fatigue and creep-fatigue tests were conducted according to ASTM specification E 606 on uniform gage-length specimens. The fatigue specimens had a specimen diameter of approximately 8.0 mm, and the gage had a slightly reduced gage section to minimize the probability of extensometer-induced crack initiation. Small punch marks (0.03 to 0.05 mm deep) were placed on the gage

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Table 1. Comparison of the chemical composition of several types of 316 stainless steel

Type	Chemical compositions (wt %)									
	C	Si	Mn	P	S	Ni	Cr	Mo	N	Others
316	≤0.08	≤0.75	≤2.00	≤0.045	≤0.030	≥10.00 ≤14.00	≥16.00 ≤18.00	≥2.00 ≤3.00	≤0.10	
316L	≤0.030	≤0.75	≤2.00	≤0.045	≤0.030	≥10.00 ≤14.00	≥16.00 ≤18.00	≥2.00 ≤3.00	≤0.10	
316FR[1]	≤0.02	≤1.00	≤2.00	≥0.015 ≤0.040	≤0.030	≥10.00 ≤14.00	≥16.00 ≤18.00	≥2.00 ≤3.00	≥0.06 ≤0.12	Al: ≤0.05 B: ≤0.001 Co: ≤0.25
316FR plate 606149	0.008	0.58	0.83	0.027	0.003	11.20	17.01	2.21	0.076	Al: 0.001 B: 0.0006 Co: 0.06
316L(N)[2]	≤0.030	≤0.50	1.60 — 2.00	≤0.025	0.005 — 0.01	12.00 — 12.50	17.00 — 18.00	2.30 — 2.70	0.06 — 0.08	Al: — B: 0.001 — 0.002 Co: <0.25

[1]Tentative specification for the Japanese Demonstration Fast Breeder Reactor.
[2]Specification for the Superphenix Fast Breeder Reactor.

surface approximately 15.75 mm apart and equidistant from the specimen gage section center to minimize the probability of extensometer slippage during long-term tests. Crack initiation did not occur at extensometer contact points. Similar test procedures were followed in Japan.

RESULTS AND DISCUSSION

Tensile tests were conducted over the temperature range of 25 to 650°C and strain rates of 10^{-7} to 10^{-3} s^{-1}. Plots of yield and tensile strength as a function of temperature and strain rate are shown in Fig. 1. Yield strength (YS) shows little or no rate dependency but decreases with increasing temperature. Ultimate tensile strength (UTS) decreases with increasing temperature and shows rate dependency, particularly at low strain rates with increasing temperature. A comparison of YS and UTS values for type 316FR and type 316 melted and tested throughout the world shows similar values (Brinkman et al., 1977). Tensile ductilities (i.e., uniform elongation and reduction of area), show decreases from near 35 and 80% to around 15 and 65%, respectively, with decreasing strain rates (10^{-3} to 10^{-6} s^{-1}) at temperatures above about 550°C.

Figure 2 compares rupture data generated to date at ORNL with data generated in Japan from 50-mm plate material from three heats with ASTM grain sizes of 4 to 6 (Kaguchi, 1998). Also shown for comparison are predictions of rupture life obtained from the Japanese-98 FME equation (Kaguchi, 1998), given as follows.

$$\log_{10}(t_R) = -23.962345 + \frac{30708.247}{T+273.15} + \frac{2914.114}{T+273.15}\log_{10}\sigma - \frac{2465.8312}{T+273.15}(\log_{10}\sigma)^2 \qquad (1)$$

where

T = temperature (°C)
$500 \le T \le 800$
σ = stress (N/mm^2)
t_R = rupture time (h)

The comparison shows good agreement between rupture data generated in Japan and at ORNL over the temperature range of 550 to 600°C. The comparison also shows that Eq. (1) fits the data reasonably well but may be conservative at long test times or low stress levels.

Figure 3 shows creep-rupture ductility, measured as reduction of area, as a function of temperature and time. The comparison shows good agreement between data obtained at ORNL and in Japan. Note also that at 550°C ductility data are strongly time dependent, but at 600°C they show less time dependency. Long-term rupture ductility for type 316 shows similar behavior with increasing time and tends to increase after long times at the lower temperature (Brinkman, 1985a). Figure 3 also shows that the ductility of type 316FR remains relatively high with increasing test times in comparison with types 304 and 316 stainless steel. Creep ductilities for type 316 and type 304 over the temperature range of 538 to 593°C can drop to values below 10% (Brinkman, 1985a). In the case of type 304, ductility values measured by reduction of area can drop continuously to values considerably below 10% as test times approach 100,000 h. High long-term creep ductility is important in that it improves resistance to creep-fatigue failure (Brinkman, 1985a).

Figure 4 compares minimum creep rate data at a given stress level from tests conducted at ORNL and in Japan for type 316FR. Again, good agreement between data sets is evident. Also shown for comparison

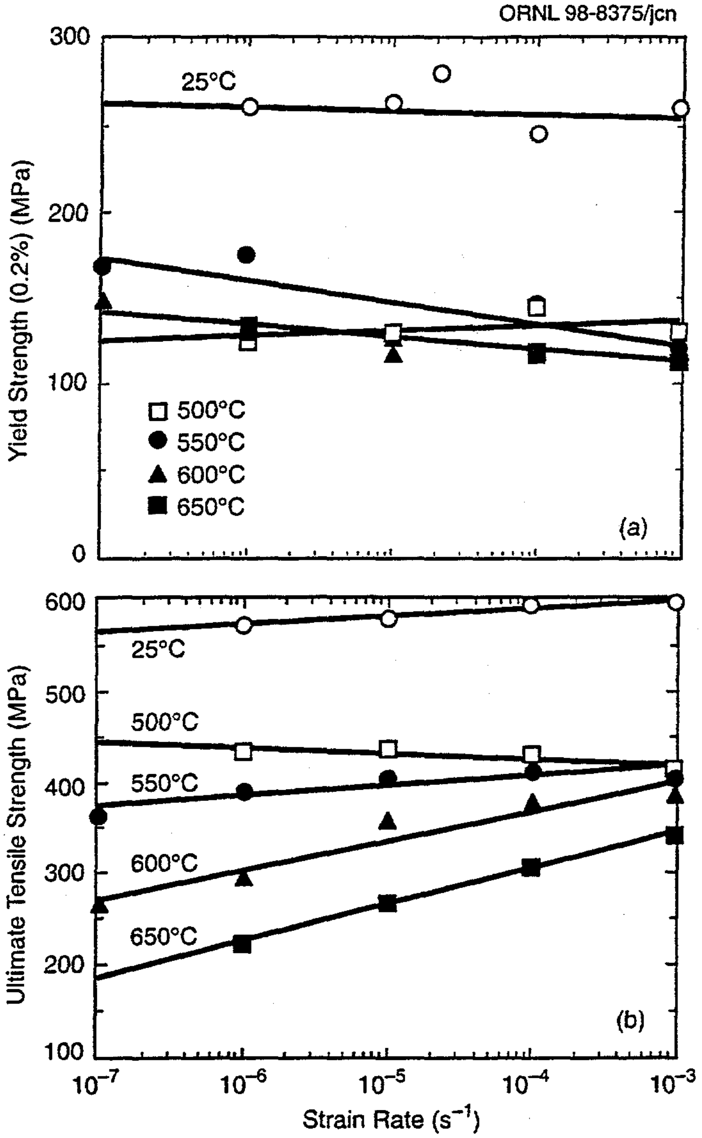

Fig. 1. Yield strength (a) and tensile strength (b) of type 316FR stainless steel as a function of temperature and strain rate.

are estimates of isothermal minimum creep rates based on the Japanese-98 FME equation (Kaguchi, 1998) given as follows.

$$\dot{\epsilon}_m = 262.24698 \cdot \exp\left[\frac{-5922.1293}{T+273.15}\right] \cdot t_R^{-1.1351216} \qquad (2)$$

where

$\dot{\epsilon}_m$ = minimum creep rate (mm/h)

The variables t_R and T are the same as defined in Eq. (1). Good agreement is apparent between the data and Eq. (2).

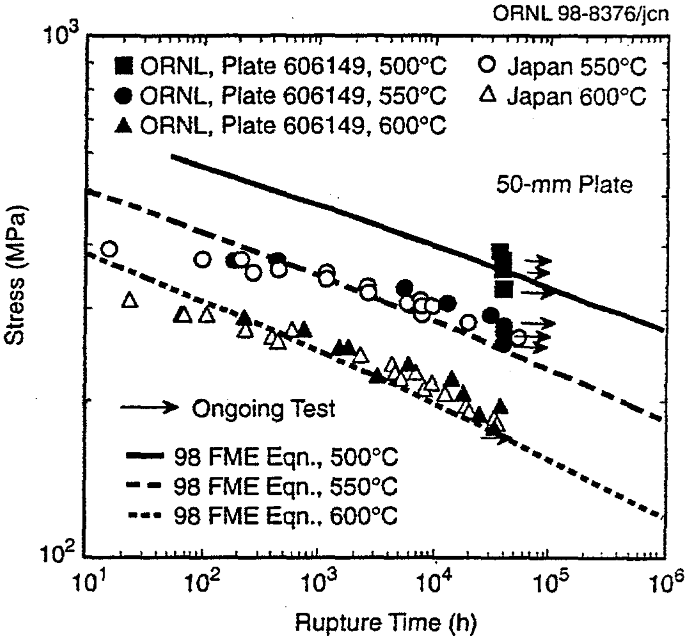

Fig. 2. Comparison of creep-rupture data for type 316FR stainless steel generated at ORNL and in Japan with predictions based on the Japanese-98 FME equation.

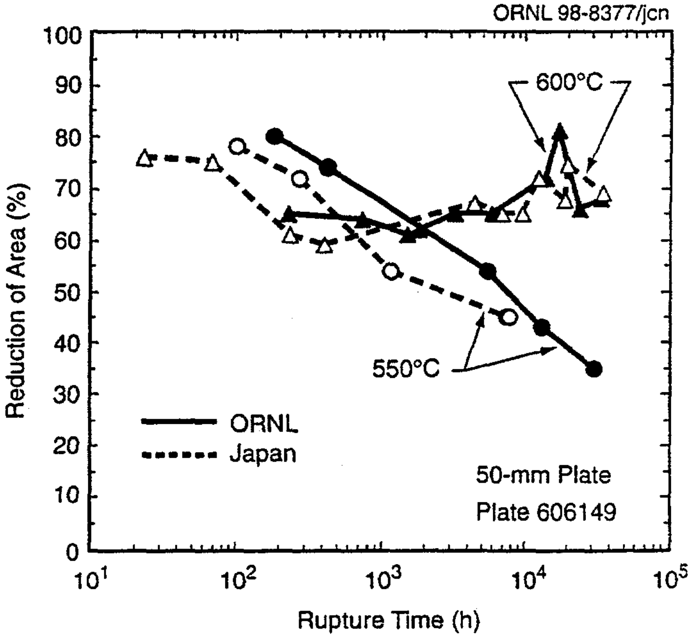

Fig. 3. Comparison of creep-rupture ductilities at two temperatures from data for type 316FR stainless steel generated at ORNL and in Japan.

Figure 5 compares several stress-rupture data sets for types 316FR and 316L(N) stainless steel generated at 500, 550, and 600°C. The 316FR data set includes data from ORNL and Japan (Kaguchi, 1998), consisting of six heats and three product forms (i.e., plate, forging, and

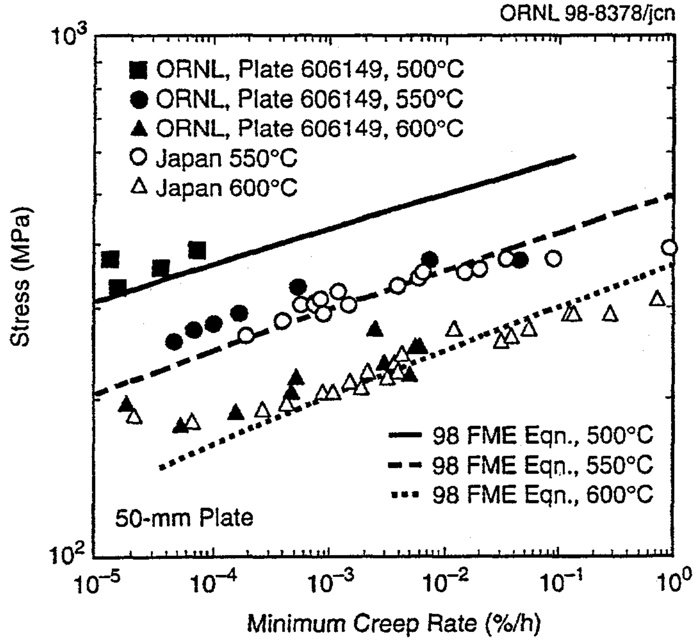

Fig. 4. Comparison of minimum creep rate data for type 316FR stainless steel generated at ORNL and in Japan with estimates based on the Japanese-98 FME equation at three temperatures.

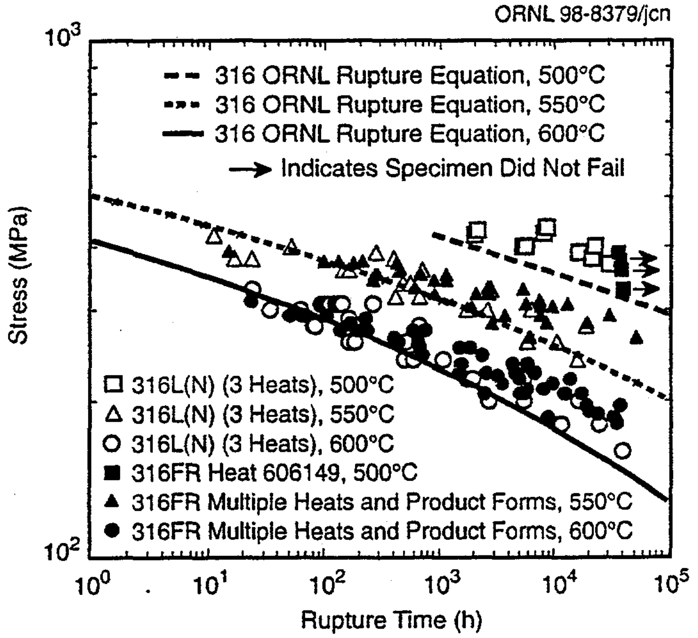

Fig. 5. Comparison of creep-rupture data for types 316FR and 316L(N) stainless steel with the ORNL creep-rupture equation for type 316 stainless steel at three temperatures.

tubing) with grain sizes varying from ASTM 3.0 to 6.9; data for 316L(N) (i.e., 30- and 50-mm plate), consisting of three heats, came from European sources (Schirra and Heger, 1990; Schirra et al., 1991). Predictions of rupture life of type 316 stainless steel based on an equation developed at ORNL for this material are shown as lines for these three temperatures as well. The equation for average behavior of type 316 is as follows.

$$\log_{10} t_R = C_h - 0.01312\sigma - 2.552\log_{10}\sigma + 20{,}880/T \qquad (3)$$

In Eq. (3), t_R is the rupture life (h), σ is the stress (MPa), and T is the temperature (K). The value C_h is the lot constant and reflects the relative strength for a given heat. The average value of C_h is -11.870 and is the value used in Eq. (3) to make estimates shown in Fig. 5. Low- and high-strength estimates can be calculated using C_h values of -12.674 and -11.065, respectively, which are simply twice the overall standard error of estimates.

The comparisons given in Fig. 5 show that type 316FR and 316L(N) have above-average rupture lives in comparison with type 316 stainless steel, particularly at low stress levels or longer test times. A similar conclusion was reached by Japanese investigators (Asada et al., 1992; Nishida et al., 1993). As Table 1 shows, the 316FR and 316L(N) with similar and optimized chemistries, primarily carbon and nitrogen to increase rupture strength and ductility (Rabbe and Heritier, 1979; Asada et al., 1992), have similar creep-rupture strengths.

Figures 6 through 8 compare strain-controlled continuous-cycle fatigue data for type 316 (Brinkman, 1985b) and 316FR stainless steel. Data for type 316FR came from tests conducted at ORNL (plate 606149) and three different heats (50-mm plate) tested in Japan (Kaguchi, 1998). Tests conducted on type 316 were run at $4 \times 10^{-3}\ \mathrm{s}^{-1}$ while tests conducted on Type 316FR were run at a strain rate of $1 \times 10^{-3}\ \mathrm{s}^{-1}$. Also shown for comparison are estimates of fatigue life given by the Japanese-98FME equation for plate and forging material (Kawasaki, 1998) expressed as follows.

$$(\log_{10} N_f)^{-1/2} = A_0 + A_1 \cdot \log_{10}\Delta\epsilon_t + A_2(\log_{10}\Delta\epsilon_t)^2 + A_3\cdot(\log_{10}\Delta\epsilon_t)^4 \qquad (4)$$

where

T = temperature (°C)

$\Delta\epsilon_t$ = total strain range
N_f = cycles to failure
$A_0 = 1.3203567 - 1.3046351 \times 10^{-7} \times T^2 \times R$
$A_1 = 8.7650102 \times 10^{-1} - 1.1381593 \times 10^{-2} \times R$
$A_2 = 3.1365177 \times 10^{-1} - 5.3062684 \times 10^{-8} \times T^2$
$A_3 = -1.6049523 \times 10^{-2}$
$R = \log_{10}\dot{\epsilon}$
$\dot{\epsilon}$ = Strain rate (s^{-1})

Figures 6 through 8 indicate that good agreement was achieved between test results obtained at ORNL and Japanese laboratories for 316FR stainless steel. When the results for both 316FR and 316 are compared, it is also apparent that fatigue lives of these two materials are essentially the same. However, differences in grain size would be expected to produce variability, particularly at the high-cycle end of the curve for a given temperature.

Figures 9 and 10 are plots of cycles to failure vs tensile hold time for types 316FR and 316 stainless steel. Hold periods of the same duration

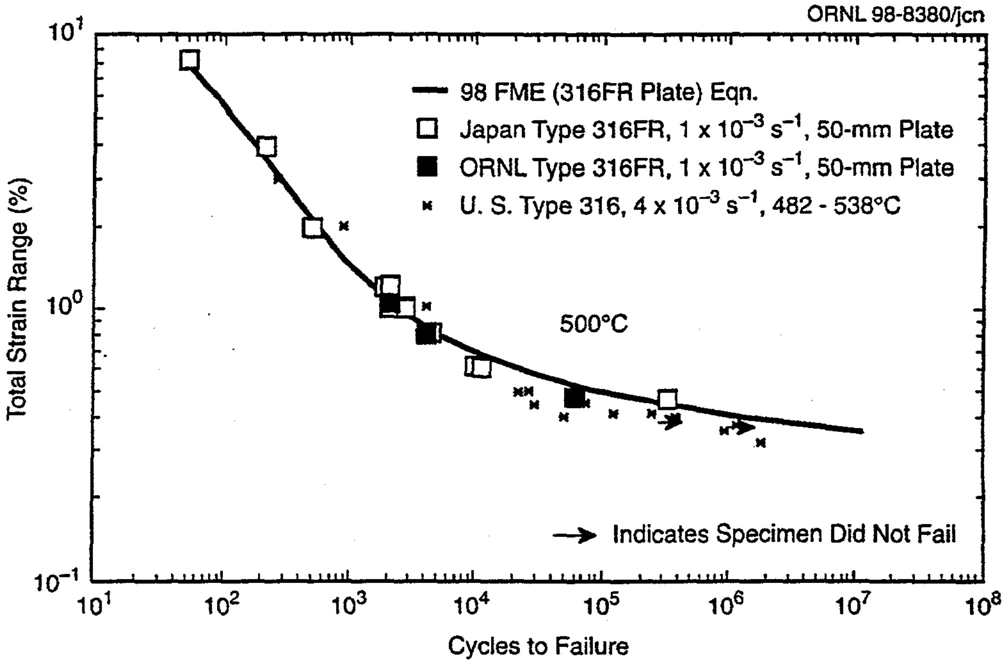

Fig. 6. Comparison of continuous-cycle fatigue data at 500°C generated at ORNL and in Japan for type 316FR stainless steel (plate and forging) with estimates based on the Japanese-98 FME fatigue equation. Data for type 316 stainless steel are also shown for comparison purposes.

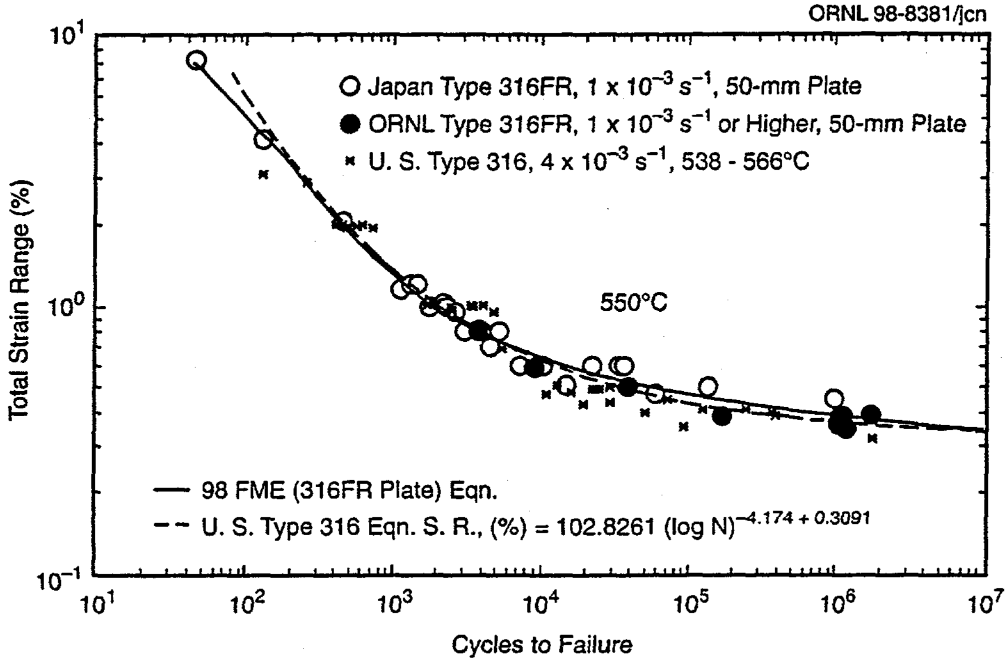

Fig. 7. Comparison of continuous-cycle fatigue data at 550°C generated at ORNL and in Japan for type 316FR stainless steel (plate and forging) with estimates based on the Japanese-98 FME fatigue equation. Data for type 316 stainless steel and an equation for this material are given for comparison purposes.

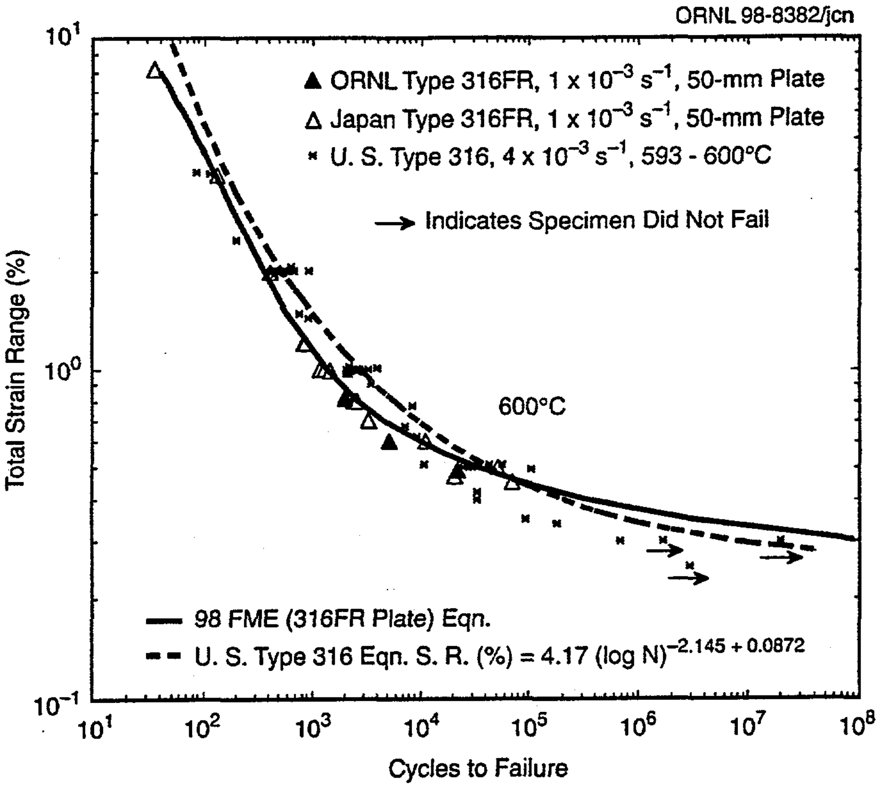

Fig. 8. Comparison of continuous-cycle fatigue data at 600°C generated at ORNL and in Japan for type 316FR stainless steel (plate and forging) with estimates based on the Japanese-98 FME fatigue equation. Data for type 316 stainless steel and an equation for this material are also given for comparison purposes.

were imposed during each cycle for tests conducted at a strain range of 1% and at the indicated temperature. The data generated at ORNL and in Japan show good agreement. Data for type 316 generated at these same temperatures came from multiple heats in the solution-annealed and pre-aged condition (Brinkman et al., 1972; Brinkman, 1985). Considerable heat-to-heat variation is apparent in the type 316 data in comparison with type 316FR data (three heats); the comparison shows improved resistance to creep-fatigue damage and less scatter for the 316FR material. Ueta et al. (1995) similarly reported improved creep-fatigue properties of type 316FR in comparison with types 304 and 316 stainless steel. This improvement was attributed to the increased resistance to intergranular failure caused by the fine, film-like Fe_2Mo precipitates present at the grain boundaries in type 316FR. Thus type 316FR with restricted and optimized chemistry has improved rupture strength, creep ductility, and creep-fatigue resistance. Thermal pre-aging of type 316 prior to testing similarly improves creep-fatigue performance as shown in Fig. 10 and elsewhere (Brinkman, 1985a). Longer hold time data and at lower strain ranges more appropriate to design conditions would be helpful to further substantiate the advantages of type 316FR over type 316 stainless steel for elevated-temperature service involving potential creep-fatigue damage in expected plant lifetimes.

CONCLUSION

Results are reported of elevated-temperature tensile, creep, continuous-cycle fatigue, and creep-fatigue tests conducted on type 316FR stainless steel. Comparisons were made with these properties and similar properties of types 316, 316L(N), and 316FR to show improved performance of the latter two optimized grades of type 316 stainless steel. Specific conclusions are as follows.

1. Tensile properties of type 316FR were similar to type 316 stainless steel with yield strength showing little strain-rate sensitivity, but ultimate strength showing increasing rate dependency over the range of 10^{-3} to $10^{-7} s^{-1}$ with increasing temperatures above about 550°C.
2. Creep and creep-rupture data generated out to times of approximately 40,000 h for type 316FR stainless steel at ORNL showed good agreement when compared with similar data generated in Japan. Long-term rupture data for both types 316FR and 316L(N) showed increased lives and ductilities over that of type 316, particularly at low stress levels appropriate to design.
3. Continuous-cycle strain-controlled fatigue data generated on type 316FR at ORNL showed good agreement with similar data generated in Japan. Type 316FR has fatigue properties similar to that of type 316 stainless steel.

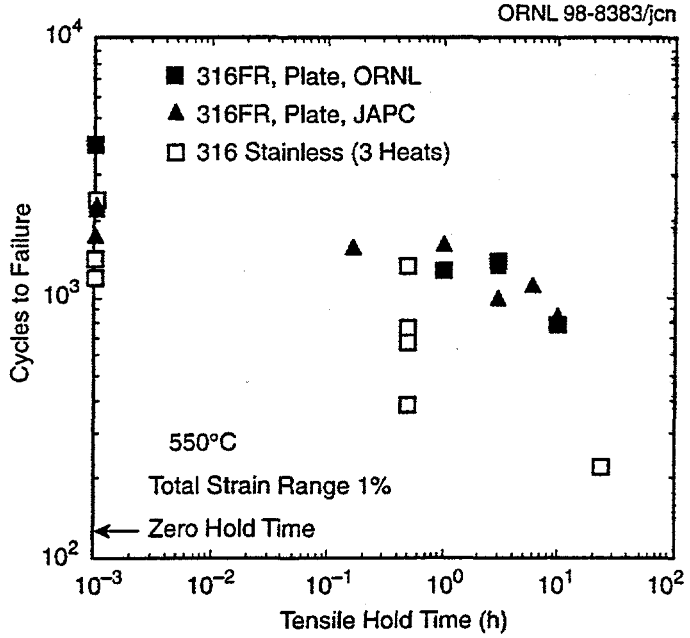

Fig. 9. Creep-fatigue data for types 316 and 316FR stainless steel generated at 550°C and at a strain range of 1%, and plotted as cycles to failure as a function of hold time.

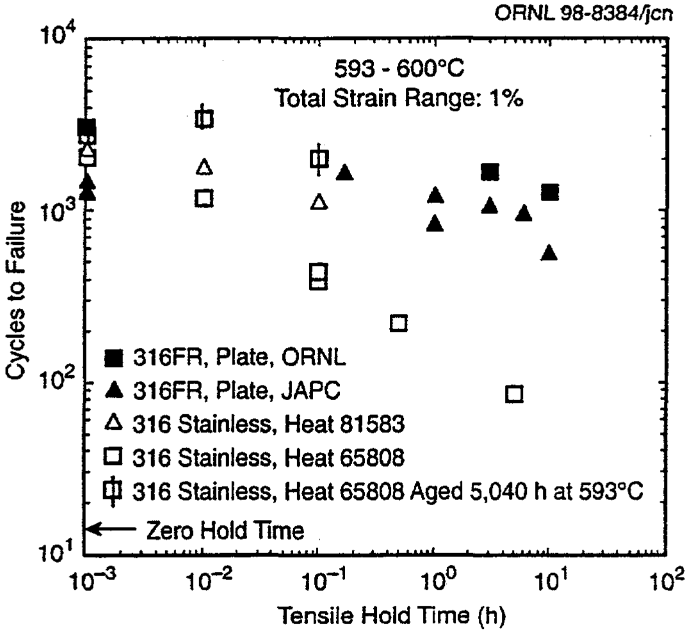

Fig. 10. Creep-fatigue data for types 316 and 316FR stainless steel generated at 593 to 600°C.

4. Creep-fatigue data generated on type 316FR were compared with data for type 316 stainless steel that had been generated at a single-strain range of 1%. Type 316FR showed improved resistance to creep-fatigue damage over that of type 316 stainless steel. This extended life was attributed to increased resistance to intergranular crack propagation as displayed by type 316FR stainless steel.

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