Fatigue Properties of Low Carbon 316 Stainless Steel under 20 MeV Proton Irradiation and Thermal-Pulse

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The high-cycle fatigue properties of low carbon 316 stainless steels, 316F with 0.04 mass%C and 316PSI with 0.001 mass%C, were investigated and compared with those of 316(ST-1) with 0.08 mass%C reported previously. Both the fatigue hardening and life decreased with carbon content, especially in 316PSI, indicating that the fatigue induced precipitates suggested for 316(ST-1) were mainly carbide or some complex of carbon-solute atoms. Effects of *in situ* 20 MeV proton irradiation or thermal-pulse were further investigated for 316F at 333~573 K. In 316(ST-1), radiation damage, i.e. the effect of irradiation after the subtraction of thermal effect, caused an enhancement of the fatigue hardening at both 333 and 573 K. In contrast, in 316F radiation damage caused a suppression of the fatigue hardening at 333 and 453 which reversed to the enhancement at 403 and 503 K, and again the suppression at 573 K. The suppression can be expected when the effects of dispersion of existing precipitates by irradiation were larger than the other effects of irradiation, and vice versa. Therefore, we consider that the fatigue induced precipitates were smaller in their size in 316F than in 316(ST-1), and in 316F the precipitates of various types probably correspond to the suppressions at 333, 453 and 573 K. The corresponding results for thermal-pulse and the results observed for the effects of *in situ* irradiation or thermal-pulse on the fatigue life were compatible with the view mentioned above.

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I. Introduction

The first wall of a fusion reactor is expected to be subjected to thermal stresses under intensive neutron irradiation⁽¹⁾⁽²⁾, i.e. repeated stresses under irradiation and thermal pulses. For the irradiation effects on the mechanical properties, many works have been done for post irradiation tests, however, *in situ* irradiation experiments have little been reported in the open literature except irradiation creep⁽³⁾. One reason for the latter fact is a limited damage rate of $10^{-7} \sim 10^{-6}$ dpa/s available for mechanical tests on bulk specimens at the present time. That is, for *in situ* irradiation with the low damage rate, the short-term mechanical properties can hardly be modified, for example, the expected effects on the low-cycle fatigue properties are too small to be observed⁽⁴⁾⁽⁵⁾. On the other hand, the low-stress rupture tests⁽⁶⁾ and high-cycle fatigue tests⁽⁷⁾ demonstrated that the long-term mechanical properties can considerably be modified by the present limited damage rate where different effects are found between the *in situ* and post irradiation tests. It is to be noted that the damage rate mentioned above is comparable with that scheduled for the first wall during reactor operations⁽¹⁾⁽²⁾. The investigation of the long-term mechanical properties under irradiation is therefore

urgently needed.

In prospect of getting an insight into the effects of *in situ* irradiation on the high-cycle fatigue properties, we started *in situ* 20 MeV (=3.20 pJ) proton irradiation tests on the solution treated 316 stainless steel, where the total-strain-controlled bending tests were carried out between room temperature (RT) and 573 K. In the previous work on 316(ST-1) with 0.077 mass%C (see Table 1 in Ref. (7) for the chemical composition), we observed the following: During the fatigue tests without irradiation, a strong fatigue hardening was observed. The close study on the fatigue hardening suggested that it was associated with the fatigue induced precipitations⁽⁸⁾⁽⁹⁾. In the preliminary tests with a damage rate of $\sim 10^{-8}$ dpa/s⁽⁷⁾, *in situ* irradiation at RT revealed an enhancement of the fatigue hardening giving an elongation of fatigue life by 2-3 times, which was found to be larger than those observed for the comparable post irradiation tests. *In situ* irradiation tests with an increased damage rate of $\sim 10^{-7}$ dpa/s revealed that the irradiation effects were larger for pulse-irradiation tests than for continuous-irradiation tests⁽⁹⁾. Since proton irradiation is expected to cause both

Table 1 Chemical composition of the materials used (mass%).

Material	C	Si	Mn	P	S	Cr	Ni	Mo	N
316F [†]	0.038	0.04	0.23	0.003	0.002	16.77	13.95	2.32	0.011
316PSI ^{††}	0.001	0.91	1.58	0.034	0.004	17.22	13.46	2.51	0.001

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radiation damage and beam heating, the effects of pulse irradiation are considered to be composed of those of radiation damage and thermal-pulse. Then the effects of pulse irradiation were compared with those of thermal pulse assuming that the effects of radiation damage can be evaluated after the subtraction of the effects of thermal-pulse from those of pulse-irradiation with the following results⁽¹⁰⁾: At 333 and 573 K, radiation damage and thermal-pulse caused an enhancement and a suppression of the fatigue hardening, respectively. The former was surmised to be due to the enhancement of fatigue induced precipitation and pile-up of irradiation-induced defects under *in situ* radiation damage and the latter, due to the dispersion of existing precipitates by enhanced dislocation motion during thermal-pulse, respectively.

In the present paper, to clarify further the fatigue induced precipitation, we investigated the effect of the carbon content on it using low carbon 316 stainless steels, 316F and 316PSI (see below). Also we carried out the *in situ* irradiation and thermal-pulse tests on 316F.

II. Experimental Procedures

The specimens used were cut from rolled sheets of 316F and 316PSI whose chemical composition is listed in Table 1. Prior heat treatments were the same as those described in Refs. (7)–(11). In review, after mechanical polishing of the specimens, they were annealed at 1370 K for 3.6 ks in a vacuum of 2×10^{-4} Pa and then quenched into water. The quenched specimens were firstly electrolytically polished in order to remove the surface layer of about 0.05 mm and simultaneously smooth out the specimen surfaces. The specimens were then annealed again at 573 K for 36 ks in a vacuum of 10^{-4} Pa to degass hydrogen possibly picked up during the electrolytical polishing. The shape of specimens was a U shaped coil of rectangular cross section with thick ends for clamping (see Fig. 1(b) in Ref. (8)). The thinner arms, about 0.12 mm thick, 0.5 mm wide and 16 mm long, were used as a reed for the flexural vibration. The grain size of specimens was typically 0.04 μm .

The fatigue testing method was almost the same as that described in Refs. (7)–(11). In review, the total strain amplitude (ε_t) controlled fatigue tests were carried out using large amplitude resonant flexural vibrations of the specimens at about 200 Hz in an atmosphere of about 10^2 PaHe. During the fatigue tests, concurrent changes in the resonant period P and the drive force DF were measured almost continuously. ε_t was maintained constant by automatically adjusting DF . DF corresponds to the internal friction in the elastic range or work done during a fatigue cycle. It is to be noted that in the elastic range, P is related to the Young's modulus M through the relationship $M \propto P^{-2}$. P in the elastic range will be referred to as P_0 hereafter. In the micro-plastic range, P increases with increasing ε_t because of an increase in the plastic strain ε_p , and at constant ε_t the changes in ε_p cause the parallel changes in P , where in a crude approximation the relationship $(P/P_0 - 1) \propto \varepsilon_p$ holds⁽¹⁰⁾. In the pres-

ent test, P_0 was measured initially at $\varepsilon_t \leq 10^{-4}$ and then ε_t was increased into the micro-plastic range between 10^{-4} and 10^{-3} by a step to start the fatigue test. During the tests P firstly strongly increased from P_0 showing a maximum P_s at several 10^3 cycles after the increase of ε_t , and then turned to decrease due to the fatigue hardening (see Fig. 1). In the following, P_s/P_0 and P/P_0 will be used to monitor an initial $(\varepsilon_p)_s$ and a concurrent ε_p during the fatigue tests.

Three types of *in situ* irradiation were carried out using 20 MeV protons at 333–573 K. In the type-I pulse-irradiation tests, the fatigue test was made with a stepwise increase in ε_t , where at each ε_t pulse-irradiation for 30 s was started after about 1×10^4 cycles following $P = P_s$ and then after about 2×10^4 cycles following the termination of pulse-irradiation ε_t was increased to the next ε_t step. Here the effects of pulse-irradiation on the fatigue hardening were investigated at the early elapsed cycles in each ε_t step. In the type-II pulse-irradiation tests, ε_t was kept constant during the whole test and pulse-irradiation for 30 s was repeated at every 300 s for the whole fatigue life. Here we investigated the influence of increasing elapsed cycles or increasing fatigue hardening on the effects of pulse-irradiation, and also the effects of pulse-irradiation on the fatigue life. The type-III irradiation tests were the ε_p -controlled fatigue tests under continuous-irradiation, where the concurrent value of P/P_0 was kept constant by adjusting ε_t , and the effects of *in situ* continuous-irradiation on the fatigue life were studied. The intensity of 20 MeV protons used was $0.02 \sim 0.03 \text{ A/m}^2$ for the type-I irradiation tests, and $0.04 \sim 0.05 \text{ A/m}^2$ for the type-II and -III irradiation tests respectively, where the intensity varied from specimen to specimen, but was kept constant within $\pm 10\%$ for each specimen. The specimens were thin enough for the complete penetration of 20 MeV protons, where with 0.025 A/m^2 , the damage rate estimated was about $1 \times 10^{-7} \text{ dpa/s}^{(12)(13)}$, and the temperature change ΔT due to beam heating observed was about 8 K. In order to investigate the effects of thermal-pulse due to beam heating separately, type-I and -II thermal-pulse tests with $\Delta T = 8 \sim 15 \text{ K}$ were made by halogen lamp light exposure (pulse-exposure, hereafter). The type-I tests were conducted at various temperatures in between 333 and 573 K and the type-II and III tests at 333 K, respectively.

III. Experimental Results and Discussion

1. The fatigue tests without irradiation

Figure 1 shows examples of the changes in P during a fatigue test without irradiation or thermal-pulse observed at 333 K in 316(ST-1), 316F and 316PSI specimens. After P_0 was measured, ε_t was increased by a step and kept constant to start the fatigue tests which were conducted with almost the same P_s/P_0 of ~ 1.2 where ε_t was 5.4 , 5.8 and 6.4×10^{-4} for 316(ST-1), 316F and 316PSI specimens, respectively. (It should be noted that the ε_t for yielding in static bending increased with car-

Fig. 1 Examples of changes in P during the fatigue tests at 333 K in the solution treated 316(ST-1), 316F and 316PSI specimens, which are shown by the curves 1 to 3, respectively. The tests were always conducted with $P_s/P_0 \approx 1.2$. The curve 1 was redrawing of the result at 323 K reported in Fig. 4(a) in Ref. (9) (see text).

bon content, i.e. it was smallest in 316PSI. The reverse relation found for the fatigue tests reflects a rapid work hardening at the early elapsed cycles.) For all specimens, during initial several 10^3 cycles P steeply increased reflecting an increase in ε_p , and then after showing a maximum (P_s), P turned to decrease due to the fatigue hardening which tended towards saturation as the fatigue test continued towards failure. In Fig. 1, one can see that in the order of 316(ST-1), 316F and 316PSI, the magnitude of fatigue hardening and fatigue life decreases. (The rapid hardening found for $\sim 10^4$ cycles after P_s in 316PSI was mainly due to work hardening.) The fatigue hardening in 316F and 316PSI was enhanced at elevated temperatures as in 316(ST-1)⁽⁸⁾⁽⁹⁾ (not shown here). Therefore the fatigue hardening in 316F and 316PSI is considered to be associated with the fatigue induced precipitation as suggested in 316(ST-1)⁽⁸⁾⁽⁹⁾. The fact that the fatigue hardening decreased with decreasing carbon content suggests that the fatigue induced precipitation of some carbide was mainly responsible for the fatigue hardening.

The TEM-observation on 316(ST-1) specimens revealed the manifestation of very fine black dots in the specimen fatigued at 573 K, which were, however, too scarce to explain the observed fatigue hardening. We therefore surmise that most fatigue induced precipitates in 316(ST-1) specimens were too fine to be resolved by TEM in heavily deformed specimens as suggested in the previous work⁽⁸⁾⁽⁹⁾. The fatigue induced precipitates in 316F and 316PSI specimens are probably smaller in both size and number density than in 316(ST-1) specimens (see III.2).

2. Effects of pulse-irradiation and thermal-pulse on the fatigue hardening in 316F

Figure 2(a) shows an example of changes in P observed in the type-I pulse-irradiation test at 333 K of 316F specimen, and was enlarged in (b). As seen in Fig. 2(b), immediately after the start of pulse-irradiation P showed

Fig. 2 (a) An example for changes in P observed at 333 K in 316F specimen where the fatigue test was conducted with increasing ε_i by steps. Here the results for $\varepsilon_i = 5.5, 6.2, 6.5$ and 6.8×10^{-4} are shown. At each ε_i , *in situ* pulse-irradiation was made using 20 MeV protons with 0.019 A/m^2 , which is denoted by ON in the figure. (b) The enlarged drawing of the part indicated by a small frame in (a) (see text).

a step-like increase $\Delta P/P$, i.e. an increase in ε_p , which was canceled by a step-like decrease in P just after the termination of pulse-irradiation. A change in the changing rate of P , $(dP/\text{cycle})/P$ by irradiation is denoted as $\Delta(dP/\text{cycle})/P$. In Fig. 2(b) the fatigue hardening was suppressed during pulse-irradiation giving $\Delta(dP/\text{cycle})/P > 0$, and a part of the reduced fatigue hardening did not recover after the termination of pulse-irradiation.

In order to investigate the effects of thermal-pulse separately, the type-I pulse-exposure tests were also carried out. In Fig. 3, $\Delta P/P$ observed in the type-I pulse-irradiation and pulse-exposure tests at 333 K are plotted against P/P_0 , where $\Delta P/P$ was normalized with $\Delta T = 8 \text{ K}$ where ΔT denotes an increase in the specimen temperature due to beam heating or pulse-exposure. One can see that $\Delta P/P$ was almost the same for pulse-irradiation tests and for pulse-exposure tests, i.e. both were due to thermal-pulse. $\Delta P/P$ due to thermal-pulse tended towards saturation with increasing P/P_0 or ε_p . The similar features were observed at the test temperatures between 333 and 573 K (see Fig. 6). Figure 4(a) and (b) show similar results for $\Delta(dP/\text{cycle})/P$ observed at 333 and 503 K. As seen in Fig. 4, $\Delta(dP/\text{cycle})/P$ also increased then tended to saturate with increasing P/P_0 , but its magnitude varied between pulse-irradiation and pulse-exposure tests and depended on the testing temperature. We evaluated the effects of radiation damage using

Fig. 3 $\Delta P/P$ vs. P/P_0 in 316F observed at 333 K for three specimens with pulse-irradiation (open symbols) and four specimens with pulse-exposure (filled symbols) (see text).

Fig. 4 $\Delta(dP/cycle)/P$ vs. P/P_0 in 316F observed at 333 K (a), and at 503 K (b). Three (at 333 K) and four specimens (at 503 K) with pulse-irradiation (open symbols). Four (at 333 K) and three specimens (at 503 K) with pulse-exposure (filled symbols).

$[\Delta(dP/cycle)/P]_{ir-th}$ which was obtained by the subtraction of $[\Delta(dP/cycle)/P]_{th}$ due to thermal-pulse from $[\Delta(dP/cycle)/P]_{ir}$ due to pulse-irradiation. The observed results of $[\Delta(dP/cycle)/P]_{th}$ and $[\Delta(dP/cycle)/P]_{ir-th}$ are shown in Fig. 7(a) and (b), respectively.

In order to study the effects of elapsed cycles on $\Delta P/P$ and $\Delta(dP/cycle)/P$, the type-II tests were carried out at 333 K with the results shown in Fig. 5(a) and (b). In the constant ϵ_t (the type-II) tests, P decreased with increasing elapsed cycles due to the fatigue hardening (see Fig. 1). In Fig. 5(a) and (b), $\Delta P/P$ and $\Delta(dP/cycle)/P$ were plotted against P/P_0 instead of the elapsed cycles, respectively, where two examples with $P_s/P_0 \approx 1.2$ are shown for

Fig. 5 (a) examples for $\Delta P/P$ vs. P/P_0 in 316F observed in the ϵ_t -controlled fatigue tests at 333 K under repeated pulse-irradiation (open symbols) and those under repeated thermal-pulse (filled symbols) where $\Delta P/P$ shown were normalized with $\Delta T=8$ K. The arrows indicate the order of repetition. The bold solid curve denotes $\Delta P/P$ found in Fig. 3 or in the type-I tests. (b) Similar to (a), but for $\Delta(dP/cycle)/P$. The bold solid and dashed curves denote $\Delta(dP/cycle)/P$ found for pulse-irradiation and that for pulse-exposure in Fig. 4(a) or in the type-I tests, respectively.

pulse-irradiation tests as well as for thermal-pulse tests. The arrows in the figures denote the direction of an increase in elapsed cycles. In Fig. 5(a), for both pulse-irradiation and pulse-exposure tests, $\Delta P/P$ in the type-II tests showed a deviator decrease from that in the type-I tests with increasing elapsed cycle. (For the type-II pulse-irradiation tests, the elapsed cycle where the first pulse-irradiation was given was larger than the corresponding one in the type-I tests. Therefore, the data for the first

Fig. 6 $\Delta P/P$ for 316F with $\Delta T=8$ K at $P/P_0=1.1$ found in Fig. 3 or that in the type-I tests are plotted against the testing temperature. $\circ$: for pulse irradiation. ∇ : for pulse-exposure. $\square$: the corresponding results due to thermal-pulse found for 316(ST-1) reported in Ref. (10). $\blacklozenge$ at 333 K denotes $\Delta P/P$ at $P/P_0=1.12$ found at prolonged elapsed cycles in the type-II pulse-exposure tests shown in Fig. 5(a). $\triangle$ denotes $\Delta P_s/P_s$ due to temperature change (see text).

pulse-irradiation in the type-II tests showed a significant deviation from the corresponding results observed in the type-I tests.) The deviatory decrease was very rapid at the early cycles and showed the tendency of saturation at the prolonged elapsed cycles where $\Delta P/P$ for pulse-irradiation agreed with that for pulse-exposure. The features remained the same in the tests with smaller P_s/P_0 except that the $\Delta P/P$ curve moved towards smaller P/P_0 on the P/P_0 axis as a whole and $\Delta P/P$ at the prolonged elapsed cycles tended to decrease towards $\Delta P_0/P_0$ (not shown here). The features seen for $\Delta(dP/cycle)/P$ in Fig. 5(b) were similar to those for $\Delta P/P$ except the following: In contrast to $\Delta(dP/cycle)/P$ in the type-I tests (the bold solid and dashed curves), that found at prolonged elapsed cycles here was larger for pulse-exposure than for pulse-irradiation.

In Fig. 6 $\Delta P/P$ (evaluated at $P/P_0=1.1$) in the type-I tests for pulse-irradiation and that for pulse-exposure are plotted against the testing temperature, together with the corresponding results for $\Delta P/P$ due to the thermal-pulse reported in 316(ST-1)⁽¹⁰⁾ and $\Delta P/P$ in 316F found after prolonged elapsed cycles in the type-II pulse exposure tests mentioned in Fig. 5(a). It can more clearly be seen that in 316F $\Delta P/P$ found for pulse-irradiation always showed a good agreement with that for pulse-exposure. The features that $\Delta P/P$ was recoverable after the termination of thermal-pulse and $\Delta P/P$ was larger at lower temperatures were very similar to those reported in 316(ST-1)⁽¹⁰⁾ except that $\Delta P/P$ was always larger in 316F than in 316(ST-1). It was also observed that in 316F $\Delta P/P$ decreased with increasing fatigue hardening (see

Figs. 5(a) and 6). The former suggests that the mechanism giving $\Delta P/P$ is common in 316F and 316(ST-1), i.e. $\Delta P/P$ is due to an increase in ε_p through an enhanced motion of dislocations surmounting precipitates. Then $\Delta P/P$ is expected to increase when existing precipitates are small in size as speculated in 316(ST-1)⁽¹⁰⁾. To clarify this issue we carried out the following measurements: The type-I tests were made but here at each ε_i , following P_s , ε_i was readily increased to the next ε_i step to minimize the fatigue hardening, and the ε_i dependence of P_s/P_0 was measured, where no pulse-irradiation nor pulse-exposure was given (not shown here). From its temperature change we evaluated $\Delta P_s/P_s$ due to the temperature change by 8 K at around $P_s/P_0=1.1$, which are shown by the symbol Δ in Fig. 6. One can see that $\Delta P_s/P_s$ found at lower temperature was much larger than $\Delta P/P$ as predicted above. The small $\Delta P_s/P_s$ found at a higher temperature dose not contradict the above prediction but suggests that the fatigue induced precipitates formed in the very early elapsed cycles were too fine to reveal the fatigue hardening at elevated temperatures.

Figure 7(a) and (b) show the similar results as those mentioned in Fig. 6, but here $[\Delta(dP/cycle)/P]_{th}$ and $[\Delta(dP/cycle)/P]_{ir-th}$ are plotted in (a) and (b), respectively, where the corresponding results reported in 316(ST-1)⁽¹⁰⁾ and those found after the prolonged elapsed cycles in the type-II tests mentioned in Fig. 5(b) are also shown. One can see that both $[\Delta(dP/cycle)/P]_{th}$ and $[\Delta(dP/cycle)/P]_{ir-th}$ found in the type-I tests of 316F were different from the corresponding ones observed in

Fig. 7 Similar to Fig. 6 but $[\Delta(dP/cycle)/P]_{th}$ due to thermal-pulses and $[\Delta(dP/cycle)/P]_{ir-th}$ due to pure radiation damage are plotted in (a) and (b), respectively. $\circ$: results observed for the type-I tests for 316F, $\square$: the redrawings of those for 316(ST-1) reported in Ref. (10). $\bullet$ at 333 K in (a) and in (b) respectively denote $[\Delta(dP/cycle)/P]_{th}$ and $[\Delta(dP/cycle)/P]_{ir-th}$ found at $P/P_0=1.14$ for prolonged elapsed cycles in the type-II tests shown in Fig. 5(b).

316(ST-1). That is, in 316F the radiation damage caused the suppression of the fatigue hardening at 333 and 453 K which reversed to the enhancement at 403 and 503 K, respectively, and again the suppression at 573 K. The effects of thermal-pulse observed in 316F also showed the characteristic temperature dependence which indicates a good correlation with that for the effects of radiation damage. On the other hand, both the effects of radiation damage and thermal-pulse found for prolonged elapsed cycles in the type-II test of 316F were comparable with those in the type-I tests of 316(ST-1).

For radiation damage the suppression of the fatigue hardening can be expected when the effects of irradiation dispersion of existing precipitates are larger than the other irradiation effects, and vice versa. The results in Fig. 7(b) appear to suggest that in 316F precipitates of various types were introduced above 333, 453 and 573 K which could be dispersed under *in situ* radiation damage at these temperatures but became to stand against irradiation dispersion at elevated temperatures due to an increase in their size, respectively. The results observed for thermal-pulse were also compatible with the above view. At present, we do not know the types of the probable various precipitates. However, it seems suggestive that the recent low cycle fatigue work on austenitic steel reported the hardening due to some complexes between carbon and chromium atoms which can be modified by silicon concentration⁽¹⁴⁾⁽¹⁵⁾. For the effects of silicon concentration on the present fatigue tests, further work is now in progress.

3. Effects of *in situ* irradiation and thermal-pulse on the fatigue life

The results mentioned in Figs. 5–7 indicate that thermal-pulse always gives rise to the suppression of the fatigue hardening. Therefore, repetition of thermal-pulse can be expected to shorten the fatigue life. On the other hand, the radiation damage caused, *e.g.* at 333 K, the suppression of the fatigue hardening at the early elapsed cycles which, however, reversed to the enhancement at the prolonged elapsed cycles. Therefore, the effects of *in situ* radiation damage on the fatigue life may be variable: For the ϵ_i controlled tests, an elongation of the fatigue life can be expected. On the other hand, for the ϵ_p controlled tests, *in situ* radiation damage can possibly cause a shortening of the fatigue life. Based on these considerations, we carried out the ϵ_i controlled fatigue tests under repeated pulse-irradiation or thermal-pulse (the type-II tests) with the results shown in Fig. 8(a) and the ϵ_p controlled tests under continuous irradiation (the type-III tests) with the results shown in Fig. 8(b), respectively. It should be noted that the tests shown in Fig. 8(b) were carried out with rather high P_{hold}/P_0 which caused heating-up of specimens due to increased work done, *e.g.* in a rough estimation ~ 50 K-up at $P_{\text{hold}}/P_0 = 1.2$ and ~ 150 K-up at $P_{\text{hold}}/P_0 = 1.4$ from 333 K, respectively. This does not, however, cause serious errors because the fatigue life is known to be insensitive to the testing temperatures⁽¹⁶⁾. In Fig. 8(a), $\bar{P}/P_0$ used was plotted against the elapsed

Fig. 8 (a) For the ϵ_i controlled tests at 333 K, $\bar{P}/P_0$ used was plotted against the elapsed cycles to failure N_f where $\bar{P}$ denotes a mean value of P during the tests. $\circ$: without irradiation or thermal-pulse, $\bullet$: with repeated pulse-irradiation, $\blacktriangle$: with repeated thermal-pulse. (b) Similar to (a), but here results for the P (or ϵ_p) controlled tests at about 333 K are shown where P_{hold} denotes the P -value used during the tests. $\circ$: without irradiation, $\bullet$: under continuous irradiation. The dashed line 1 in (a) and (b) is tentatively fitted to the results without irradiation or thermal-pulse, and the dash-dotted line 2 in (b) to the results under irradiation (see text).

cycles to failure N_f , where $\bar{P}$ denotes the mean P -value during the test. In Fig. 8(b), we plotted P_{hold}/P_0 against N_f , where P was kept constant at P_{hold} during the tests.

In spite of the limited number of the data shown in Fig. 8(a) and (b), one can see that the above-mentioned prediction appeared to be confirmed. That is, repeated thermal-pulses shorten the fatigue life. On the other hand, for continuous irradiation tests one can see, in general, shortening of the fatigue life at higher P_{hold}/P_0 (or ϵ_p) and elongation at lower P_{hold}/P_0 . The results in Fig. 8(a) and (b) are rather limited, but demonstrate the significant effects of *in situ* irradiation and thermal-pulse on the fatigue properties.

IV. Conclusion

The high-cycle fatigue properties of low carbon 316 stainless steels, 316F with 0.04 mass%C and 316PSI with 0.001 mass%C, and effects of *in situ* 20 MeV proton irradiation and thermal-pulse on the fatigue properties of 316F were investigated at temperatures between 333 and 573 K. In our previous work in 316(ST-1) with 0.08 mass%C, a strong fatigue hardening observed during the tests was surmised to be associated with the fatigue induced precipitation. The fatigue hardening with similar features was again observed for 316F and 316PSI but its magnitude decreased with decreasing carbon content, suggesting that the fatigue hardening is mainly associated with fatigue induced carbides or some complex of carbon-solute atoms. The effects of radiation damage and thermal-pulse at the early elapsed cycles of the fatigue tests observed in 316F were different from those in 316(ST-1). For 316(ST-1), the radiation damage and thermal-pulse always caused the enhancement and suppression of the fatigue hardening, respectively. In contrast, for 316F, the radiation damage caused the suppression of the fatigue hardening at 333, 453 and 573 K suggesting an increased effect of irradiation dispersion of existing precipitates at these temperatures. At these temperatures, the suppression reversed to the enhancement at 403 and 503 K, suggesting that in 316F precipitates or complexes of various types came to grow from around 333, 453 and 573 K. The observed results for thermal-pulse were compatible with this view.

The influence of increasing elapsed cycles on the effects of radiation damage and thermal-pulse in 316F was investigated at 333 K with the following results: Thermal-pulse always caused the suppression of the fatigue hardening but its magnitude decreased with increasing elapsed cycle. On the other hand, for radiation damage, the suppression of the fatigue hardening found at the early elapsed cycles reversed to the enhancement at the prolonged elapsed cycles. The results were surmised to reflect a growth of the fatigue induced precipitates with increasing fatigue cycle. From these results, one can ex-

pect that thermal-pulse repeatedly given during the tests may shorten the fatigue life. On the other hand, the effects of *in situ* radiation damage on the fatigue life may be variable depending on whether irradiation dispersion of existing precipitates are the predominant effect of radiation damage or not. These effects of irradiation and thermal-pulse on the fatigue life were further investigated at 333 K and the results obtained were compatible with the above conjecture.

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