Effects of *in situ* Pulse-Irradiation of 20 MeV Protons and Thermal-Pulse on the Fatigue Properties of 316 Stainless Steel

By H. Mizubayashi*, H. Kikuchi**, H. Ohtaka***,
S. Okuda* and Y. Tagishi****

Effects of 20 MeV proton pulse-irradiation and light pulse-exposure on the fatigue properties of solution treated 316 stainless steel were investigated using the large amplitude internal friction technique with about 200 Hz at 333 and 573 K. The light pulse-exposure caused a thermal-pulse in specimens. *In situ* thermal-pulse during the total strain (ϵ_t) controlled tests with $\epsilon_t \approx 10^{-4} \sim 10^{-3}$ caused a step-like increase in the plastic strain ϵ_p at first, followed by a decrease in the fatigue hardening rate. The step-like increase in ϵ_p was reversible and therefore was surmised to be associated with an enhancement of dislocation motion surmounting obstacles. On the other hand, the decrease in the fatigue hardening rate did not recover after a stop of the light exposure; therefore it was surmised to be associated with a decrease in the number density of fatigue induced precipitates. The proton pulse-irradiation had two effects; one caused a step-like increase in ϵ_p , which was found to be due to thermal-pulse caused by beam heating. Another was an intrinsic effect of irradiation which was revealed by a subtraction of the effects of thermal-pulse. This intrinsic effect of irradiation or radiation damage-pulse was an enhancement of the fatigue hardening rate, which was much larger than that observed for continuous-irradiation. This increase in hardening rate due to radiation damage-pulse was found to largely cancel out the decrease in hardening rate due to thermal-pulse. The present results demonstrate that dynamic irradiation and thermal-pulse could cause significant changes in the fatigue properties of the potential fusion reactor materials.

(Received October 18, 1989)

Keywords: 316 stainless steel, fatigue properties, *in situ* irradiation test, pulse-irradiation, thermal-pulse

I. Introduction

The first wall of a fusion reactor is expected to be subjected to thermal stresses under intensive neutron irradiation. For the irradiation effects on the mechanical properties, many works have been done for post irradiation experiments, however, *in situ* irradiation experiments are scarce in the open literatures except irradiation creep⁽¹⁾. The one reason for the latter fact is a limited damage rate of $10^{-7} \sim 10^{-6}$ dpa/s available for *in situ* irradiation experiments for bulk specimens at the present time. That is, for conventional low-cycle fatigue tests, expected effects of *in situ* radiation damage are too small to be observed⁽²⁾⁽³⁾. On the other hand, for rupture tests in a relatively low stress range⁽⁴⁾ and high-cycle fatigue tests⁽⁵⁾, it has been reported that *in situ* irradiation caused detectable changes in the mechanical properties. The latter results suggest that *in situ* irradiation is expected to give rise to considerable changes in the long-term fatigue properties.

In our preliminary work⁽⁵⁾, we started the high-cycle fatigue test of solution treated 316 stainless steel under 20 MeV[†] proton irradiation with a damage rate of

$\sim 10^{-8}$ dpa/s. *In situ* irradiation at room temperature revealed irradiation hardening which caused an elongation of fatigue life by 2 ~ 3 times. The effects of *in situ* irradiation were found to be larger than those observed for the comparable post irradiation tests. Furthermore, *in situ* irradiation tests with an increased damage rate of $\sim 10^{-7}$ dpa/s revealed that irradiation effects were larger for *in situ* pulse-irradiation tests than for tests under continuous-irradiation⁽⁶⁾. Since proton irradiation is expected to cause both radiation damage and beam heating, the effects of pulse irradiation are considered to be composed of those of radiation damage and thermal-pulse. In the present paper, we investigated these effects on solution treated 316 stainless steel separately.

II. Experimental Procedures

The specimens used were cut from a rolled sheet of type 316 stainless steel and their chemical composition and prior heat treatments were the same as those described in Refs. (5)–(7). 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

* Institute of Materials Science, University of Tsukuba, Tsukuba, Ibaraki 305, Japan.

** Graduate Student, University of Tsukuba. Present address: Hitachi Metals Ltd., Tokyo 100, Japan.

*** Student, University of Tsukuba. Present address: Hitachi Ltd., Tokyo 101, Japan.

**** Tandem Accelerator Center, University of Tsukuba.

[†] 20 MeV $\approx$ 3.20 pJ.

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. (7)). The thinner arms, about 0.12 mm thick, 0.5 mm wide and 18 mm long, were used as a reed for the flexural vibration. The grain size of specimens was typically 0.04 mm.

The fatigue testing method was almost the same as that described in Refs. (5)–(7). 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 . It is noted that in the elastic range, P is related to the Young's modulus M through the relationship $M \propto P^{-2}$. 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 , changes in ϵ_p cause parallel changes in P . DF corresponds to internal friction.

In situ irradiation tests were performed using 20 MeV protons of about 0.02 A/m^2 at 333 and 573 K, here the pulse-irradiation for about $3 \times 10^2 \text{ s}$ was made during the fatigue tests. The specimen was thin enough for the complete penetration of 20 MeV protons, where an increase in temperature of the specimen (ΔT) due to beam heating was several Kelvins, which was estimated in the similar way as will be described for Fig. 3. In order to investigate the effects of thermal pulse separately, the halogen lamp light pulse-exposure was made instead of 20 MeV proton pulse-irradiation, where the thermal-pulse of several Kelvins was given to the specimen during the fatigue test.

III. Experimental Results

Figure 1(a) shows an example of the concurrent changes in P observed during the fatigue test at 333 K without proton irradiation or thermal-pulse, and in Fig. 1(b), the control of ϵ_t during the test is schematically depicted. (It is to be noted that an increase in P corresponds with a decrease in maximum stress in the ϵ_t -controlled tests, therefore in Fig. 1(a) an increase in P was plotted downwards.) As shown in Fig. 1, firstly P in the elastic range was measured, i.e. P_0 with ϵ_{t0} ($=0.7 \times 10^{-4}$ here), and then ϵ_t was increased and kept constant at the testing ϵ_{t1} ($=5.2 \times 10^{-4}$ here). During the increase in ϵ_t to ϵ_{t1} , P increased because of an increase in ϵ_p . After ϵ_t was kept constant at ϵ_{t1} , P further increased for initial several 10^3 cycles and then, reversed to decrease showing a maximum at P_s . The decrease in P (hereafter, the fatigue hardening) was rapid at first and tended towards saturation with increasing number of cycles. After prolonged vibrations, P started to increase again and the specimen failed. In previous works^{(5)–(7)}, we reported that the fatigue hardening was associated with the fatigue induced precipitations, and the increase in P just before the specimen failure was caused by the reduction of cross-

Fig. 1 (a) An example of changes in P observed during the fatigue test of the solution treated 316 stainless steel at 333 K, and (b) a schematic drawing of the change in ϵ_t during the test. $\epsilon_{t0} = 0.7 \times 10^{-4}$, $\epsilon_{t1} = 5.2 \times 10^{-4}$ and $P_s/P_0 = 1.08$ (see text).

Fig. 2 ϵ_t dependence of P_s/P_0 observed for fatigue tests of solution treated 316 stainless steel, □ at 333 K and ○ at 573 K.

sectional area of the specimen due to crack propagation. We will investigate effects of proton irradiation on the fatigue hardening later on.

In Fig. 2, P_s/P_0 observed for fatigue tests of various specimens without proton irradiation or thermal-pulse are plotted against ϵ_t . It is seen in Fig. 2 that in the present micro-plastic range, P_s/P_0 increased linearly with increasing ϵ_t for both testing temperatures. This result suggests the relationship $(P_s/P_0 - 1) \propto (\epsilon_p)_s$ above the elastic limit ($\approx 4 \times 10^{-4}$ at 333 K and 2×10^{-4} at 573 K for the present specimens). Therefore, we surmised that in a crude approximation, the relationship $(P/P_0 - 1) \propto \epsilon_p$ holds. In the following, P_s/P_0 and P/P_0 will be used to monitor an initial $(\epsilon_p)_s$ and a concurrent ϵ_p during the

Fig. 3 (a) An example of effects of 20 MeV proton pulse-irradiation on P during the fatigue test at 333 K. $P_s/P_0 = 1.14$ and $\varepsilon_t = 7.2 \times 10^{-4}$. ON shows proton irradiation with 0.024 A/m^2 . (b) Similar to (a) but at 573 K. $P_s/P_0 = 1.16$ and $\varepsilon_t = 5.4 \times 10^{-4}$ (see text).

fatigue tests.

Figure 3(a) and (b) show examples of the results of the fatigue tests at 333 and 573 K with repeated 20 MeV proton pulse-irradiations, respectively. For the fatigue tests with proton pulse-irradiation, a beam intensity at the specimen was firstly monitored from an increase in P in the elastic range due to beam heating, i.e. an increase in P_0 (ΔP_0) due to pulse-irradiation for $\varepsilon_t = \varepsilon_{t0}$ (see Fig. 1). From the $\Delta P_0/P_0$ and the temperature dependence of P_0 , $(dP_0/dT)/P_0 = 2.1 \times 10^{-4}/\text{K}$ between 333 and 573 K, we estimated the temperature increase ΔT due to beam heating. In the present experimental condition, $\Delta T \approx 8 \text{ K}$ for proton pulse-irradiation with 0.025 A/m^2 . After the measurement of ΔP_0 with ε_{t0} , ε_t was increased to the testing ε_{t1} and then, proton pulse-irradiation was made as shown in Fig. 3(a) and (b). For the fatigue tests at 333 K (see Fig. 3(a)), proton pulse-irradiation caused a step-like increase in P (denoted by $\Delta P/P$) at first and then a change in the time dependent fatigue hardening rate (denoted by $\Delta(dP/\text{cycle})/P$). After interruption of pulse-irradiation, following a step-like decrease in P the ordinary fatigue hardening came back where $\Delta P/P$ showed complete recovery in this step-like decrease, but the fractional part of the fatigue hardening suppressed during irradiation did not recover. The suppression of the fatigue hardening due to proton pulse-irradiation caused a shortening of the fatigue lives. For the fatigue tests at 573 K (see Fig. 3(b) and Ref. (6)), the ordinary fatigue hardening was enhanced (note an enlarged scale for the ordinate in Fig. 3(a)). Proton pulse-irradiation at 573 K also caused a step-like increase and decrease in P at the start and interruption of irradiation, respectively,

Fig. 4 (a) $\Delta P/P$ and (b) $\Delta(dP/\text{cycle})/P$ observed for repeated proton pulse-irradiation for various specimens. $\circ$ for $P_s/P_0 = 1.09$, $\square$ 1.11, $\triangle$ 1.12 and ∇ 1.14 at 333 K, and $\bullet$ 1.09, $\blacksquare$ 1.13, $\blacktriangle$ 1.14 and $\blacktriangledown$ 1.16 at 573 K (see text).

but hardly modified the time dependent fatigue hardening rate. In the following, we will investigate the effects of proton pulse-irradiation using the step-like changes in P , $\Delta P/P$, and the changes in the time dependent fatigue hardening rate $\Delta(dP/\text{cycle})/P$ which were evaluated at the early stage of pulse-irradiation (see $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ indicated for the second pulse-irradiation in Fig. 3(a)).

Figure 4(a) and (b) show respectively $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ observed for repeated proton pulse-irradiation for four specimens at 333 K and four specimens at 573 K, where $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ plotted are the values normalized at $\Delta T = 8 \text{ K}$ by correcting the effect of ΔT estimated at $\varepsilon_t = \varepsilon_{t0}$ [†]. In Fig. 4, followings can be seen: $\Delta P/P$ is, in general, smaller at 573 K than at 333 K. As the general trends, at each temperature $\Delta P/P$ increases with increasing P_s/P_0 showing saturation, and in each specimen $\Delta P/P$ tends to decrease with increasing elapsed cycles. $\Delta(dP/\text{cycle})/P$ at 333 K shows the general tendency of increase with increasing P_s/P_0 showing saturation, and in each specimen it tends to decrease with increasing elapsed cycle. On the other hand, $\Delta(dP/\text{cycle})/P$ at 573 K is always very small in its magnitude. These results suggest that, in general, $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ varies with increasing elapsed cycles, P_s/P_0 and temperatures. Then, we further investigated

[†] The beam current was kept constant within $\pm 5\%$ during pulse-irradiation and for repeated pulse-irradiation on each specimen, but was variable in the range between 0.018 and 0.025 A/m^2 among specimens. For the latter, we calibrated the observed results assuming the linear relationship between magnitudes of $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ and the beam current.

Fig. 5 An example of results showing effects of proton pulse-irradiation on P at various ε_t 's observed in one specimen at 333 K, where ε_t was increased by steps as indicated in the figure and at each ε_t , pulse-irradiation (with 0.022 A/m^2) was started after 5×10^4 cycles following each increase in ε_t . The pulse width is shown by a horizontal bar ON.

Fig. 6 $\Delta P/P$ observed for the fatigue tests with increasing ε_t (see Fig. 5). (a) at 333 K and (b) at 573 K. Δ and ∇ for proton pulse-irradiation and $\circ$ and $\square$ for halogen lamp pulse-exposure (see text).

$\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ at constant elapsed cycles below.

Figure 5 shows an example of the fatigue test at 333 K with increasing ε_t by steps, where at each ε_t proton pulse-irradiation was started after about 5×10^4 cycles following an increase in ε_t . Similar fatigue tests with increasing ε_t were made at 333 and 573 K for proton pulse-irradiation and for halogen lamp pulse-exposure with the results shown in Figs. 6 and 7. It is noted that the fatigue tests with halogen lamp pulse-exposure were made to investigate effects of thermal-pulse separately, where the thermal-pulse given to the specimens was $\Delta T \approx 5 \sim 6 \text{ K}$. In Fig. 6(a), $\Delta P/P$ at 333 K is plotted against P/P_0 for two specimens for pulse-irradiation and two specimens for pulse-exposure, and in Fig. 6(b), $\Delta P/P$ at 573 K is

Fig. 7 Similar as Fig. 6 but for $\Delta(dP/\text{cycle})/P$.

shown, where P/P_0 is that observed just before the start of each pulse-irradiation or pulse-exposure. Figure 7(a) and (b) show the similar results as those shown in Fig. 6 (a) and (b) but for $\Delta(dP/\text{cycle})/P$. In these figures, $\Delta P/P$ and $\Delta(dP/\text{cycle})/P$ plotted were those normalized at $\Delta T = 8 \text{ K}$. The results shown in Fig. 6 indicate that at both temperatures, $\Delta P/P$ shows a good agreement between pulse-irradiation and pulse-exposure, i.e. $\Delta P/P$ for both cases was caused by thermal-pulse. Also, the general tendency of increase in $\Delta P/P$ with increasing P/P_0 and the saturation behavior at higher P/P_0 can be seen more clearly. The results seen in Fig. 7 show that $\Delta(dP/\text{cycle})/P$ is, in general, larger for pulse-exposure than for pulse-irradiation. For pulse-exposure, $\Delta(dP/\text{cycle})/P$ increases with increasing P/P_0 showing the tendency of saturation for both temperatures, and is larger at 573 K than at 333 K, but for pulse-irradiation it is smaller at 573 K than at 333 K. These results shown in Figs. 4, 6 and 7 will be discussed later.

IV. Discussion

The step-like change in P , $\Delta P/P$, will at first be discussed. The results mentioned for Fig. 6 indicate that $\Delta P/P$ observed for pulse-irradiation was caused simply by thermal-pulse due to beam heating. Figure 8(a) is redrawings for the general P/P_0 dependence of $\Delta P/P$ observed in Fig. 6(a) and (b), i.e. a bold solid curve for 333 K and a bold dashed curve for 573 K, and those for $\Delta P/P$ shown in Fig. 4(a) (shown by data points), where arrows for the latter results indicate the order of repetition of pulse-irradiation. In Fig. 2, we have shown the effect of temperature on the ε_t dependence of P_s/P_0 . From the results, we can estimate $\Delta P_s/P_0$ for $\Delta T = 8 \text{ K}$ at a constant ε_t assuming a linear change in P_s/P_0 with temperatures between 333 and 573 K, which is shown by a bold dashdotted line above $P/P_0 = 1.1$ in Fig. 8(a). $\Delta P/P$

Fig. 8 (a) Redrawings for the general P/P_0 dependence of $\Delta P/P$ shown in Fig. 6(a) and (b), a bold solid curve at 333 K and a bold dashed curve at 573 K, and those of $\Delta P/P$ shown in Fig. 4(a) (data points). Arrows indicate the order of repetition for repeated pulse-irradiation. See text for a bold dashdotted line. (b) Similar to (a) but for $\Delta(dP/\text{cycle})/P$.

due to thermal-pulse observed for the process of the fatigue hardening is larger than $\Delta P_s/P_0$ which corresponds to $\Delta P/P$ expected for without the fatigue hardening (Fig. 8(a)), and shows complete recovery after interruption of thermal-pulse (Fig. 3). It appears that the fatigue-induced dislocation structures at a certain temperature are probably disturbed by a dynamic change in the temperature. Therefore, we surmise that $\Delta P/P$ due to thermal-pulse is associated with thermally enhanced dislocation motion surmounting precipitates. On the other hand, $\Delta P/P$ due to thermal-pulse is smaller at 573 K than at 333 K (Fig. 8(a)), and $\Delta P/P$ observed at various elapsed cycles with a constant ε_t (Fig. 4(a)), in general, tends to decrease with increasing elapsed cycles. Combining these results with the fact that the fatigue induced precipitation proceeds with increasing elapsed cycles and is larger at 573 K than at 333 K (see Fig. 3 and Ref. (6)), one can say that the thermally enhanced dislocation motion surmounting precipitates is larger for the initial stage of precipitation but tends to decrease with an increase in the fatigue induced precipitation. The saturation behavior of $\Delta P/P$ at higher P/P_0 probably suggests that this effect of thermal-pulse tends to saturate at higher ε_p .

In contrast to $\Delta P/P$, $\Delta(dP/\text{cycle})/P$ for thermal-pulse[†] gives rise to the permanent suppression of the frac-

tional part of the fatigue hardening (Fig. 3). In previous study⁽⁶⁾, we have reported that for the same material as used here, permanent suppression of the fatigue hardening can be expected through cutting of the fatigue induced precipitates by moving dislocations. Therefore we surmise that the suppression of the fatigue-induced hardening rate due to thermal-pulse is associated with a decrease in the number density of the fatigue induced precipitates due to enhanced dislocation motion. Then, the fact that $\Delta(dP/\text{cycle})/P$ for thermal-pulse is larger at 573 K than at 333 K (Fig. 7) can be explained as follows: The result shown in Fig. 2 suggests that for the fatigue test with the same P_s/P_0 , a maximum stress applied to the specimen is lower at 573 K than at 333 K, i.e. a minimal size of the fatigue induced precipitates resistible against cutting by moving dislocation is smaller at 573 K than at 333 K. Therefore one can expect that enhanced dislocation motion can cause more softening at 573 K than at 333 K. A relatively large difference between two specimens for $\Delta(dP/\text{cycle})/P$ due to thermal-pulse at 573 K seen in Fig. 7(b) possibly indicates that the effect of thermal-pulse is more sensitive for detailed conditions of the specimen at 573 K than at 333 K.

$\Delta(dP/\text{cycle})/P$ for pulse-irradiation is smaller than that for thermal-pulse (Fig. 7), and is smaller at 573 K than at 333 K (Figs. 7 and 8(b)). This fact suggests that for $\Delta(dP/\text{cycle})/P$, the thermal effect of pulse-irradiation is apparently canceled by the effect of pure radiation damage or atomic collisions. Further, for $\Delta(dP/\text{cycle})/P$ due to pulse-irradiation shown in Fig. 8(b), the results for 333 K indicate that $\Delta(dP/\text{cycle})/P$ observed for various elapsed cycles (Fig. 4(b)) decreased with increasing elapsed cycles. These facts suggest a close correlation between $\Delta(dP/\text{cycle})/P$ and the fatigue induced precipitation for both thermal-pulse and pulse-irradiation. Then we evaluate $\Delta(dP/\text{cycle})/P$ due to purely radiation damage-pulse, $[\Delta(dP/\text{cycle})/P]_{\text{rd}}$, assuming the following relationships:

$$[\Delta(dP/\text{cycle})/P]_{\text{rd}} = [\Delta(dP/\text{cycle})/P]_{\text{pulse-irrad.}} - [\Delta(dP/\text{cycle})/P]_{\text{thermal-pulse}} \quad (1)$$

Fig. 9 shows $[\Delta(dP/\text{cycle})/P]_{\text{rd}}$, evaluated using values of $[\Delta(dP/\text{cycle})/P]_{\text{pulse-irrad.}}$ and $[\Delta(dP/\text{cycle})/P]_{\text{thermal-pulse}}$ determined between $P/P_0=1.05$ and 1.10 in Fig. 7. It can be seen that the radiation damage-pulse caused an enhancement of the fatigue-induced hardening and the enhancement is larger at higher temperature. It is noted here that proton continuous-irradiation caused the enhancement of the fatigue induced hardening⁽⁵⁾, however, the enhancement was much less than that observed here for pulse-irradiation even after taking into account a change in the dpa-rate. Indeed, the fatigue tests under continuous-irradiation with a comparable beam intensity as that used here (not shown here) revealed much less enhancement of the fatigue induced hardening than those shown in Fig. 9.

For the effect of *in situ* radiation damage, one can expect an enhancement of atomic diffusion, pile-up of irradiation-induced defect-clusters and irradiation dis-

[†] It should be noted that for the fatigue tests with comparable thermal-pulse on annealed Cu specimens where the fatigue induced precipitation can not be expected, $\Delta(dP/\text{cycle})/P$ was hardly observed (not shown here).

Fig. 9 $\Delta(dP/cycle)/P$ due to radiation damage-pulse, $[\Delta(dP/cycle)/P]_{rd}$, evaluated from the results shown in Fig. 7 (see text).

persion of existing precipitates. The enhancement of the fatigue-induced hardening shown in Fig. 9 suggests that the former two are predominant here for both temperatures. The fact that the enhancement of the fatigue-induced hardening due to radiation damage is larger at 573 K than at 333 K is surmised to reflect that a minimal size of the fatigue induced precipitates responsible for the fatigue hardening is smaller at 573 K than at 333 K. The results in Fig. 7 show that the softening effects by dispersion of precipitates due to thermal-pulse are largely canceled by the hardening effects by enhanced precipitation due to radiation damage-pulse. A detailed mechanism to explain these results is not known yet, however, the present results demonstrate that the fatigue properties of the potential materials could strongly be modified by dynamic irradiation and temperature-change. To clarify their effects, a further work is now in progress.

V. Conclusion

Effects of *in situ* 20 MeV proton pulse-irradiation and those of thermal-pulse on the concurrent changes in the vibrational resonant period P of the specimen during the total strain (ϵ_t) controlled fatigue tests at about 200 Hz with $\epsilon_t \approx 10^{-4} \sim 10^{-3}$ were investigated on solution treated 316 stainless steel at 333 and 573 K. Thermal-pulse caused an instantaneous softening or a step-like increase in P , $\Delta P/P$, at first which was followed by a decrease in the hardening rate or an increase in $\Delta(dP/cycle)/P$. These increases in both $\Delta P/P$ and $\Delta(dP/cycle)/P$ increased

in magnitude with increasing plastic strain ϵ_p showing saturation at higher ϵ_p . $\Delta P/P$ for thermal-pulse was reversible and was larger than that expected for static temperature effect in isothermal tests. Further it appeared to become smaller with an increase in the fatigue-induced hardening, therefore it was surmised to be due to an increase in ϵ_p associated with thermally enhanced dislocation motion surmounting precipitates. On the other hand, $\Delta(dP/cycle)/P$ for thermal-pulse was not reversible and therefore was surmised to be associated with a decrease in the number density of the fatigue induced precipitates through enhanced dislocation motion. $\Delta P/P$ observed for proton pulse-irradiation was found to be the same as that for pulse-exposure of light and therefore, it is simply caused by thermal-pulse due to beam heating. A different behavior from thermal-pulse was found for $\Delta(dP/cycle)/P$. The subtraction of $\Delta(dP/cycle)/P$ for thermal-pulse from that for pulse-irradiation revealed an enhancement of the fatigue hardening rate due to radiation damage-pulse. This enhancement was much larger than that for proton continuous-irradiation, and surmised to cancel largely the effect of thermal-pulse on $\Delta(dP/cycle)/P$. The present results present the important problem that *in situ* pulse-irradiation and thermal-pulse could considerably modify the fatigue properties of the potential fusion reactor materials.

Acknowledgment

This work is partly supported by the Grant-in-Aid for Fusion Research from the Ministry of Education, Science and Culture, Japan.

REFERENCES

- (1) K. Ehrlich; J. Nucl. Mater., **133/134** (1985), 119.
- (2) J. Weertman and W. V. Green: J. Nucl. Mater., **97** (1981), 254.
- (3) A. M. Ermi and B. A. Chin: J. Nucl. Mater., **103/104** (1981), 1505.
- (4) S. Schneider, K. Herschbach, L. Shafer, M. Schirra, Ch. Wassilew and K. Ehrlich: KfK-report 3505 (1983), 147.
- (5) H. Mizubayashi, S. Okuda, K. Nakagome, H. Shibuki and S. Seki: Trans. Japan Inst. Metals, **25** (1984), 257.
- (6) H. Mizubayashi, K. Ikezaki, S. Okuda and J. M. Roberts: Trans. Japan Inst. Metals, **28** (1987), 463.
- (7) H. Shibuki, H. Mizubayashi and S. Okuda: Trans. Japan Inst. Metals, **27** (1986), 673.