Journal of Nuclear Materials 122 & 123 (1984) 391-401
North-Holland, Amsterdam

PULSED FLUX EFFECTS ON RADIATION DAMAGE

E. P. SIMONEN,[1] N. M. GHONIEM[2] and N. H. PACKAN[3]

[1]Pacific Northwest Laboratory, Richland, WA 99352
[2]University of California at Los Angeles, Los Angeles, CA 90024
[3]Oak Ridge National Laboratory, Oak Ridge, TN 37831

Pulsed irradiation fluxes can cause alteration in the development of irradiation microstructures when compared to steady irradiation microstructures. Theoretical analysis of irradiation damage development and examination of pulsed ion irradiation microstructures have indicated conditions for expected pulsing effects on fusion reactor materials. In pure metals, high instantaneous damage rates and pulse annealing periods comparable to defect relaxation times can cause significant pulsing effects. In addition, irradiation affected phases in alloys are altered by pulsed irradiation compared to steady irradiation.

1. INTRODUCTION

Inertial Confinement Fusion (ICF) and some magnetic fusion reactor designs are based on irradiation cycles of repeated irradiation and annealing periods. Such pulsed irradiation flux modifies irradiation microstructures when compared to microstructures produced by steady irradiation flux. Irradiation microstructures and physical properties of structures in these reactors may not be accurately extrapolated from steady irradiation experiments.

Mechanisms for pulsed flux effects have been proposed and pulsed ion irradiations have demonstrated specific effects in metals and alloys.[1] The mechanisms have been evaluated by calculating responses of point defects and defect aggregates to intermittent irradiation and annealing cycles. Instantaneous effects on microstructure are perturbed by pulsing and hence the integrated microstructural evolution is modified. Pulsed irradiation effects for ICF, magnetic confinement fusion and heavy ion bombardment have been modeled.

Pulsed ion irradiations and post irradiation microstructural examinations have been used to demonstrate specific examples of pulsed flux effects. Pulsing effects on precipitate phase stability and large changes in swelling and interstitial loops have been observed in a stainless steel alloy.[2] In nickel, pulsing at frequencies greater than 100 Hz produced significant changes in void number density.[3,4] Furthermore, pulsing at high temperatures produced enhanced coarsening in nickel[5] and suppressed void formation for conditions that readily produced voids during steady irradiation in an austenitic stainless steel alloy.[6] Pure metals pulsed at moderate pulsing times and temperatures have generally exhibited subtle microstructural responses to pulsing.

In addition to flux pulsing, instantaneous damage rate is an important characteristic of a fusion irradiation environment. Structural components in tokamak and mirror fusion reactors are expected to function under a peak dose rate of 10^{-12} to 10^{-6} dpa/s. On the other hand, the first walls of ICFRs should be designed to handle instantaneous damage rates of 0.1 to 10 dpa/s. However, the average displacement rate at the first wall of the various concepts is approximately the same even though the instantaneous rate is vastly different.[1]

43

In this paper, we have reviewed the theoretical descriptions and experimental examinations of pulsed flux effects but not pulsed temperature effects on microstructure. The magnitudes of predicted and measured pulsing effects are subsequently related to properties of fusion reactor structures.

2. PULSED FLUX MECHANISMS

The pulsing theories of defect aggregation are based on two approaches. First, comprehensive evaluations of point defect diffusion and aggregate size distributions have predicted pulsed effects on the nucleation, growth and coarsening of defect aggregates.[7-10] Second, approximate evaluations of effects on average void sizes have been used to establish sensitivities of microstructures to pulsed irradiation and material parameters.[10,11] Furthermore, effects of pulsed point defect production on network dislocation climb[12-16] and solute distribution have been calculated.[17]

2.1. Point Defect Diffusion

Interstitial, C_i, and vacancy, C_v, concentrations are described by the following rate equations.

$$\frac{dC_i(t)}{dt} = P - \alpha C_i C_v - Z_i \rho_d D_i C_i \qquad (1)$$

$$\frac{dC_v(t)}{dt} = P - \alpha C_i C_v - Z_v \rho_d D_v C_v$$

P and α are the defect production rate and the recombination constant, respectively. Z and D are the defect bias factor and diffusivity, respectively. It is assumed that the dislocation density, ρ_d, is the only sink.

Recombination can be neglected in Eqs. 1 if $4P < Z_i Z_v D_i D_v \rho_d^2/\alpha$.[18] The rate Eqs. 1 are then decoupled and can be treated exactly. If mutual recombination can not be neglected, Eqs. 1 can no longer be decoupled. Sizman[18] and Abromeit and Poerschke[19] have obtained approximate solutions to the rate equations by defining distinct time regimes in the build-up of the vacancy and interstitial concentrations from their initial thermal equilibrium values to their steady-state values. The cycling of the irradiation is assumed to have a period T_f, with on-time T_{on}, so that the off-time is $(T_f - T_{on})$.

The rate Eqs. 1 have been solved[14] analytically for sink dominant and recombination dominant conditions and for short and long vacancy relaxation times, $\tau_v = 1/Z_v \rho_d D_v$. Simple analytical expressions for $C_i(t)$ and $C_v(t)$ during pulsing can be found in Reference 14 for each of the above conditions.

For sink dominant conditions, the defect concentrations behave differently for short and long vacancy lifetimes. When the vacancy lifetime is short ($\tau_v < T_f$), vacancies rise rapidly to the steady state concentration during the irradiation period and decay rapidly to the equilibrium concentration during the anneal period. The interstitial response is similar to the vacancy response for sink dominant and short vacancy lifetimes. When the vacancy lifetime is long ($\tau_v > T_f$), vacancies have insufficient mobility to migrate to sinks during the pulse anneal period. Thus, the retention of vacancies from previous pulses causes the time average vacancy concentration to accumulate with each additional irradiation pulse as shown in Fig. 1a.

Likewise for recombination dominant conditions, the defect concentrations have dissimilar responses for short and long vacancy lifetimes. When vacancy lifetimes are long ($\tau_v > NT_f$), the vacancy concentration accumulates during irradiation periods and remains constant during annealing periods as shown in Fig. 1b. N is the number of pulse cycles. The interstitial concentration declines during irradiation and vanishes during annealing. When vacancy lifetimes are short ($\tau_v < T_{on}$), the steady state vacancy concentration is achieved during each irradiation period and decays during each anneal period as shown in Fig. 1c. Because the

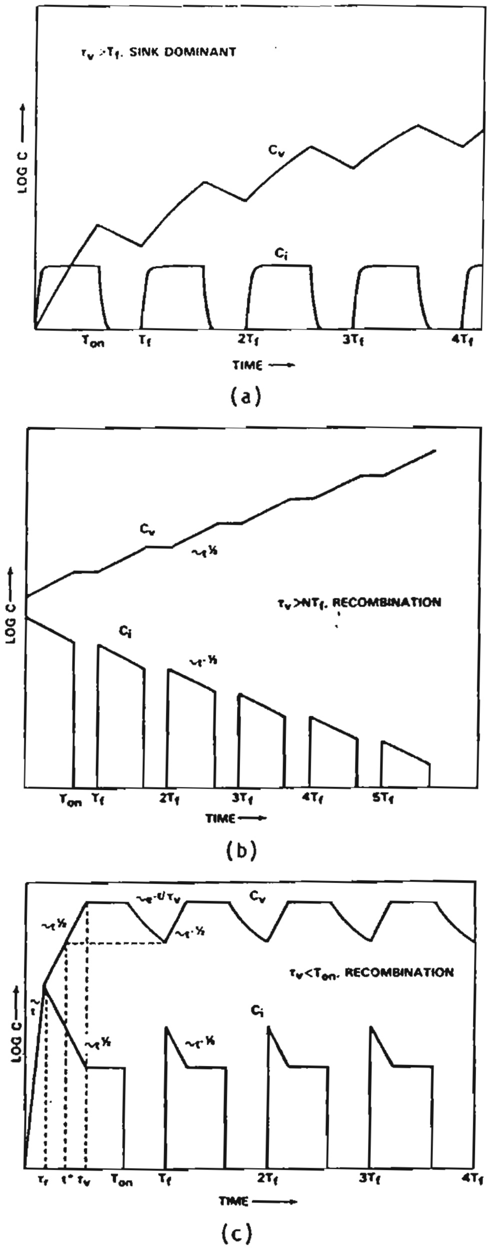

FIGURE 1
Schematic plot of vacancy and interstitial concentrations during pulsing for the indicated recombination or sink dominance and short or long vacancy lifetime.[14]

interstitial concentration is limited by recombination with vacancies, the interstitials react to changes in vacancy concentration during irradiation and vanish during annealing.

2.2. Pulsed Effects on Size Distributions

The agglomeration of point defect clusters during steady and pulsed irradiation are described by a set of rate equations for the time-dependent concentration of cluster sizes.[7] Pulsing effects on the clustering of both interstitial atoms and vacancies can then be studied by solving the equations for given pulsed irradiation conditions.

The development of the early stages of interstitial loop size distributions is shown in Fig. 2 for an ICF with high instantaneous damage rate, an accelerator with an intermediate instantaneous damage rate, and steady irradiation with a low instantaneous damage rate.[7] It is evident that higher assumed damage rates predicted smaller average loop sizes. On the other hand, the total loop concentration increased for the higher displacement damage rates. The predicted loop concentration was much higher for ICF conditions than for pulsed accelerators and steady irradiation. Damage rate differences and not pulse anneal differences caused the pulsing effects at 773 K shown in Fig. 2.

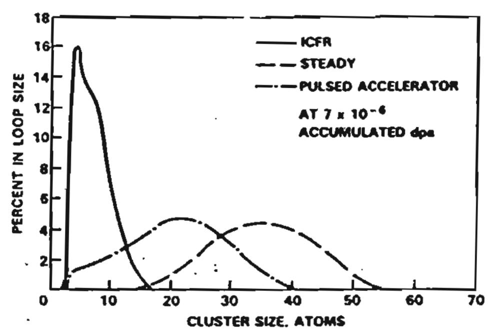

FIGURE 2
Interstitial loop size distributions in two pulsed systems and one steady system.[7]

Predicted nucleation and growth of voids were also influenced by pulsed irradiation effects on void embryo and void size distributions. Pulse annealing periods comparable to the void embryo relaxation times caused a throttling of the predicted void nucleation rate.[8] Pulse annealing periods comparable to supercritical void annealing times increased predicted coarsening rates.[10] The shape of the size distribution was altered by pulsing. However, the size distribution may be affected more strongly by diffusional broadening[20] during both pulsed and steady irradiation than by the periodic anneal for pulsed irradiation only.

2.3. Effects on Average Sized Voids

Pulsing effects on the growth of an average sized void have been calculated to establish the sensitivity of microstructure to pulsed irradiation and material parameters. For ICF, pulse compression, i.e., high damage rates for short times, caused the principal pulsing influence. For magnetic fusion and heavy ion bombardment, interpulse annealing caused the principal pulsing influence.

Pulse compression caused enhanced recombination rates and interpulse annealing caused void shrinkage for assumed ICF pulsing conditions at high temperatures. Suppressed void growth during ICF pulsing was calculated using analytical[21] and numerical[11] predictions of single pulse effects.

The zero-growth time between ICF pulses for a constant time-averaged damage rate of 10^{-6} dpa/second was calculated[11] as a function of temperature and is shown in Fig. 3. The irradiation conditions for zero growth of 1 nm, 5 nm and 10 nm radii voids are indicated. The instantaneous damage rate and the necessary microexplosion energy per shot varied with the time between pulses to keep the time-averaged damage rate fixed at 10^{-6} dpa/second. Infrequent, large ICF pellet burns resulted in the greatest suppression in calculated void growth. Shorter

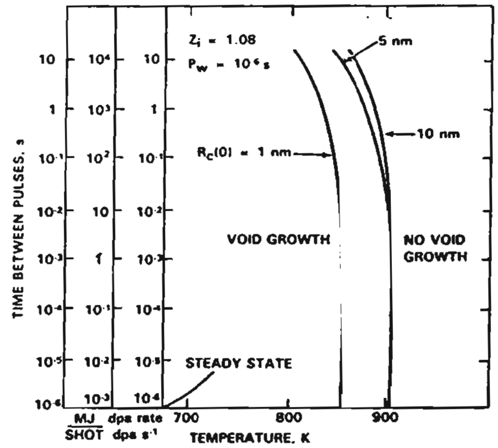

FIGURE 3
Critical void radius, $R_c(0)$, as a function of irradiation kinetics and temperature. Irradiation kinetics expressed as time between pulses, MJ/shot (pulse) and instantaneous dpa rate. Interstitial bias is 1.08 and pulse width is 10^{-6} seconds.[11]

critical times were predicted at higher temperatures because void shrinkage during annealing was faster at higher temperatures.

Analytical modeling of multiple pulses also demonstrated reduction in void growth at low pulse frequencies and high irradiation temperatures.[21] Void growth as a function of temperature and pulse frequency is shown in Fig. 4. The increase in void radius increased with increasing pulse frequency and approached the steady irradiation behavior at high pulse frequencies. Pulsing did not inhibit the void growth behavior at low temperatures because the effect of pulse compression on recombination rates decreased at lower temperatures and void annealing kinetics were negligible at temperatures below 750 K.

Calculated pulsing effects for magnetic fusion and heavy ion irradiation conditions showed lesser pulsing influences than for ICF conditions.[10] The instantaneous damage rates for magnetic fusion irradiation and heavy ion irradiation are similar to steady irradiation

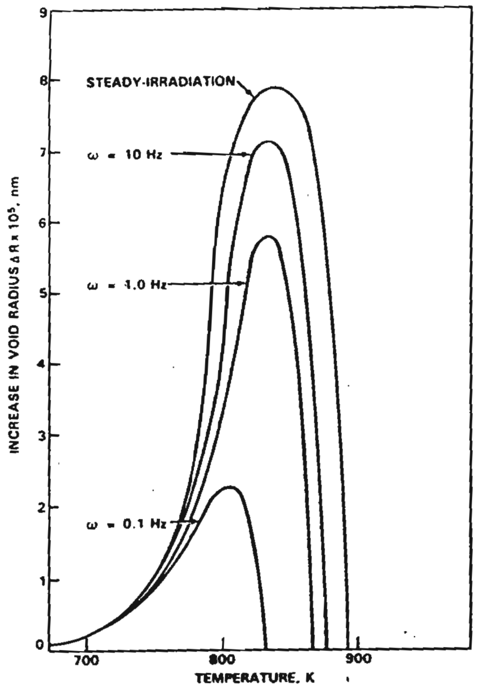

FIGURE 4
Effect of pulse frequency and temperature on increase in void radius.[21]

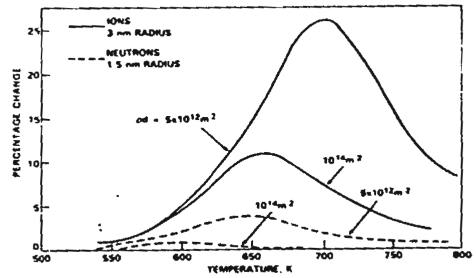

FIGURE 5
Percentage change in void radius as a function of temperature and dislocation sink strength, ρ_d, for pulsed ions and pulsed neutrons.[10] The assumed void radius is 3 nm or 1.5 nm.

damage rates conventionally used in experiments. Therefore, the pulsing influence derives from the interpulse anneals and not instantaneous damage rates for magnetic fusion and heavy ion irradiations.

Intermittent vacancy annealing affected the calculated[10] change in void size in nickel for magnetic fusion and heavy ion irradiation conditions as shown in Figure 5. The assumed pulse irradiation/anneal cycle was 1000 s/100 s for magnetic fusion neutron irradiation and was 10 s/10 s for heavy ion irradiation. The pulsing maximum effect was greater for heavy ion bombardment (5×10^{-3} dpa/second) compared to neutron bombardment (10^{-6} dpa/second). Higher dislocation densities resulted in lesser calculated pulsing effects.

The pulsing effect was observed to be significant only for conditions that allowed a large calculated build up of vacancies during the irradiation cycle and subsequent annealing during the annealing cycle. A maximum effect was predicted at a temperature less than the temperature for peak swelling in nickel.

Enhanced rates of microstructural development caused by pulsing were calculated when depleted zone production and annealing were evaluated.[1,22] The increase in damage efficiency was a consequence of vacancy emission and annihilation during the annealing cycle. The depleted zone influence was predicted only at intermediate temperatures at which high zone concentrations could dissolve during the anneal period.

2.4. Network Dislocation Climb

Pulsed effects on recombination affected both climb glide creep rates and SIPA creep rates.[12] Furthermore, sequential arrival of interstitials and vacancies at dislocations produced calculated cyclic climb during pulsing. The pulsing-induced, cyclic climb released pinned dislocations faster than for steady irradiation but only for dislocation obstacle sizes less than a few Burgers vector magnitudes.[13]

Furthermore, the cyclic climb caused by flux pulsing may not exceed the magnitude of climb fluctuations caused by local production of cascades.[23] If cascade fluctuations dominate, then pulsing should not enhance the climb glide creep rates compared to steady irradiation rates.

2.5. Solutes

Pulsed effects on calculated solute segregation indicated that long anneal times allowed relaxation in radiation induced solute segregation profiles.[17] Signficant pulsing influences were calculated only when the pulse duration was much less than the build up time for defects and defect complexes to steady state. The dependence of pulsing effects on the number of pulse cycles indicated that calculations of single pulse effects may not predict multiple cycle effects on solute segregation. The number of cycles required to achieve steady state pulsing conditions was calculated. Longer pulse duration for fixed damage rate required fewer pulses to achieve steady state. Also, higher damage rates for fixed pulse duration required fewer pulses to achieve steady state.

2.6. Precipitates

The pulsed segregation theory[17] predicted that growth of irradiation induced precipitates caused by solute redistribution should be retarded during pulsing compared to steady irradiation. The pulse annealing period allowed back flow of solutes in a direction opposite to the irradiation driving force. Therefore, precipitation processes that require nonequilibrium segregation should be retarded by irradiation pulsing. Furthermore, Lee et al.[2] have suggested that pulsing may affect precipitates by allowing more reprecipitation of precipitates dissolved by cascade induced dissolution. Solute elements ejected from the precipitate may diffuse back into the precipitate more rapidly during the pulse/anneal cycles than during steady irradiation.

3. PULSED FLUX EVIDENCE

3.1. Pulsed Effects in Pure Metals

Pulsed effects on nickel[3-5,24] and molybdenum[25] microstructures have been observed when compared to microstructures produced by steady irradiation. For nickel, the effect was strongest for high frequency pulsing at which frequencies the pulsing had its greatest influence on the population of subcritical sized voids. For low frequency pulsing, the pulsing effect was only significant at very high temperatures at which temperatures the pulse anneal influenced the supercritical sized voids.

High-frequency, rastered pulsing of nickel indicated a large decrease in void size and a large increase in void number density when compared to steady irradiation.[3] Furthermore, the effect was greater at lower temperatures. The rastered irradiation pulses were 100 Hz. Within each 2.5×10^{-3} second irradiation pulse there were 50 subpulses. Temperatures ranging from 638 to 1048 K were examined.

Another high frequency pulsing experiment in nickel was done at 10 milliseconds of irradiation and 10 milliseconds of annealing at 773 K.[4] The observed effect using 10 millisecond pulsing was opposite to that observed using high-frequency, rastered pulsing. A decrease in void number density and an increase in void size was observed when compared to steady irradiation.

The low frequency pulsing experiments in nickel indicated little or no pulsing effects below 900 K but significant effects above 900 K.[5] The pulse cycle was 10 seconds of irradiation and 10 seconds of annealing. An evaluation of the calculated supercritical size distribution indicated that the observed effects were caused by intermittent enhanced coarsening during the pulse annealing periods.[10] At these pulse times and temperatures, the subcritical size distribution was readily annealed out during the annealing period but easily reestablished during the irradiation period so little effect on the void nucleation behavior was observed.

Pulsed experiments on previously irradiated nickel containing voids indicated measurable pulsing effects on the dose dependence of void number density and size.[24] The experiments on these prevoided microstructures demonstrated that void growth as well as nucleation was affected by pulsing in nickel. Samples were pulse irradiated at 773 K for pulse cycles lasting several seconds and for pulse irradiation times that were 20%, 50% and 90% of the total cycle time. Compared to steady irradiation behavior, the 20% cycle resulted in a lesser void growth rate, the 50% cycle resulted in an enhanced growth rate and the 90% cycle had negligible effect on void growth.

Pulsed irradiation of molybdenum at temperatures from 1023 to 1223 K demonstrated that pulsing delays the sequence of void nucleation and growth but increases loop growth compared to steady irradiation behavior.[25] Total void volume was not significantly affected by pulsing compared to steady irradiation. Previous annealing experiments[26] of irradiated molybdenum suggested that loop coarsening occured at the pulse irradiation temperature. Therefore, it was not established if the pulsed effect on loop size was an effect of irradiation induced growth or an effect of thermally induced coarsening.

3.2. Pulsed effects in alloys

Pulsed 1 MeV electron irradiation on an Fe-15 wt% Cr-25 Ni ternary alloy at 873 K (for doses of 1-5 dpa) sharply reduced the mean void size and increased the void concentrations compared to steady irradiation.[27] The net effect was a reduced swelling rate relative to continuous irradiation. Swelling rate was reduced more for lower pulse frequencies and longer pulse annealing periods. Lack of cascades or thin-foils used for electron irradiation may have perturbed cavity numbers and sizes compared to heavy ion studies that use thicker specimens.

Pulsed irradiation altered the usual steady irradiation influence of helium on cavity formation. Pulsing together with simultaneous or preimplantation of helium in amounts (10-20 appm He/dpa) pertinent to fusion first wall materials has been explored. Several studies[2,6,28,29] used a simple austenitic alloy called "P7": Fe-17 wt% Cr-16.7 Ni-2.5 Mo-0.005 C. The alloy remains single phase to relatively high dose. Comparing first pulsing versus continuous irradiation with no added helium,[29] the influence of pulsing was found to be strongly temperature dependent. The influence was negligible in the region well below the peak swelling temperature (~840 K) but pronounced near the high temperature cutoff for swelling (1023 K): large cavities were present after continous 4 MeV Ni^{++} irradiation but no cavities were seen after either "fast" (1 s on/1 s off) or "slow" (60 s on/60 s off) pulsed Ni^{++} irradiation.

With helium added by either prior or simultaneous implantation, there was again both little influence of pulsing at 840 K and a strong effect at 1023 K. Whereas helium plus continuous irradiation at 1023 K resulted in bimodal cavity size distributions, only the small cavities were found after pulsed irradiation.[6] For helium preimplantation these small cavities were nearly the same for either pulsed or continuous irradiation, but with simultaneous helium injection their mean size was increased somewhat for either pulsing period. At 938 K, near the peak swelling temperature, an intriguing effect of pulsing was observed.[28] Without helium, cavities ~50-60 nm in diameter numbering 2-4 x 10^{20} m^{-3} were generated by either continuous or pulsed irradiation. For continuous irradiation, adding helium raised the concentration five fold and reduced the mean size to 35 nm (dual beam) or 19 nm (preinjected)-a quite conventional behavior. However, with fast or slow pulsed

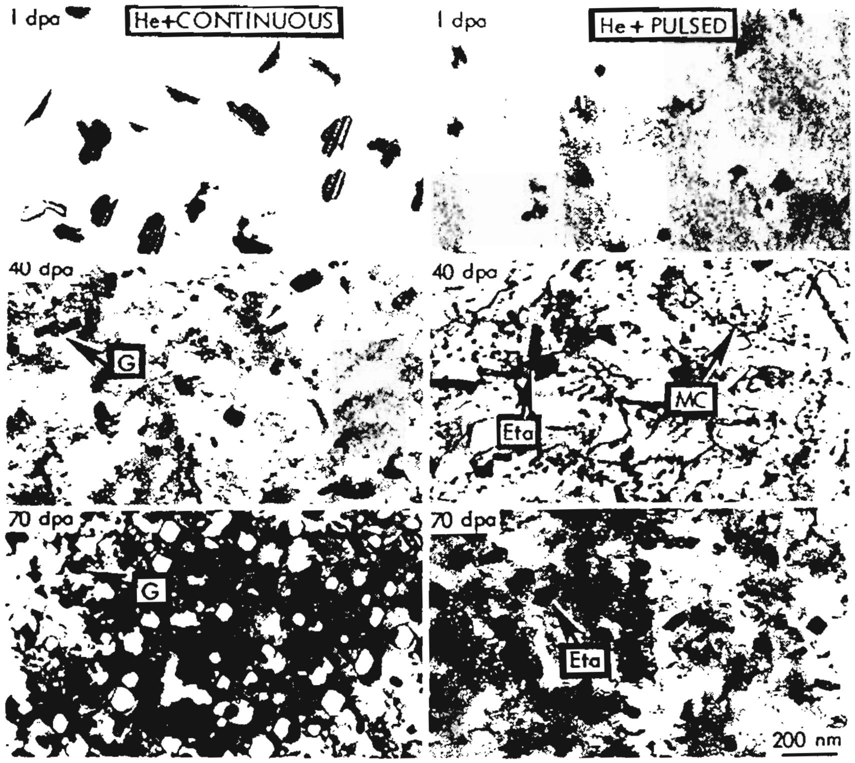

FIGURE 6
Comparison of helium plus continuous irradiation or plus pulsed irradiation as a function of dose for an austenitic stainless steel alloy containing 0.2 wt% Ti at 950 K. Differences in precipitation are indicated.[2]

irradiation plus helium, this stimulation of cavity numbers was apparently annulled. For the dual beam specimens the cavity mean diameters also were unchanged (~50 nm), though they were reduced to ~20 nm for preinjection.

Pulsed experiments showed that more complex alloys have additional interdependent paths of microstructural development that can be affected by pulsing. Strong pulsing and helium effects have recently been reported in complex, low-swelling alloys illustrated in Fig 6. Both Lee et al.[2] and Hishinuma[30] et al. have investigated the influence of pulsed relative to continuous bombardment, with and without simultaneous helium injection, in Ti-stabilized austenitic stainless steels, both near the peak swelling temperature ~950 K. Firstly, pulsing was found in each case to reduce the size of the dislocation loops seen at 1 dpa. Secondly, pulsing delayed to higher dose the supplanting of fine, thermally-stable MC phase by coarse, radiation-induced G phase. Lee et al.'s alloy (Fe-15Cr-15Ni-2Mo-2Mn-1Si-0.2Ti-0.05C) exhibited more delay than Hishinuma et al.'s which had only 0.14 wt% Ti. Pulsing plus helium further supported MC stability and caused the eta phase (less rich in Si and Ni) to form instead of G phase.[2,30] Accompanying and probably resulting from the delayed replacement of MC by massive precipitates was a postponement (to >70 dpa) in the appearance of large voids.

Small cavities-probably bubbles-were present for all cases but they were smaller for pulsing as seen in Fig. 6.

4. FUSION REACTOR MATERIALS

4.1 Sensitivity to Irradiation Parameters

The theoretical and (in some cases) experimental evaluations reviewed above indicate that pulsed flux effects on microstructure are more significant at higher dose rates, higher temperatures and longer anneal times. At high ICF dose rates, point defect concentrations are large. Large point defect concentrations result in more mutual recombination and more nucleation of interstitial loops for pulsed ICF irradiation than for steady irradiation. Heavy ion induced defect concentrations are also large. Hence both ICF and heavy ion induced microstructures were predicted to be more influenced by irradiation anneal pulses than for fusion neutron pulsing at dose rates near 10^{-6} dpa/second. Calculations indicated that pulsed heavy ion irradiation effects should exaggerate pulsed fusion results at lower dose rates.

Higher temperatures and longer annealing times allow greater recovery of nonequilibrium conditions established by irradiation. Therefore, a reduced average rate of defect aggregation and subsequent effects on properties are predicted for pulsed magnetic fusion conditions compared to steady conditions near and above half the melting temperature. Microstructures are more sensitive to pulsing at lower doses at which aggregate sizes are smaller and annealing rates are faster.

4.2 Pulsed Effects on Properties

4.2.1 Swelling

For ICF pulsing compared to steady irradiation, swelling is expected to be suppressed at high temperatures, for long pulse anneal times and for high pellet yields,[11] as seen in Fig. 3. The effect of ICF pulsing frequency on calculated increases in void radius, shown in Fig. 4 also demonstrated that longer anneal times for lower frequency pulsing reduced void growth.[21]

For pulsed operation of magnetic fusion reactors, interpulse annealing should not significantly enhance void coarsening or void growth at expected operating temperatures.[10] Significant coarsening effects were predicted and observed only at temperatures above realistic reactor operating temperatures. Calculated effects on void growth caused by vacancy annealing during pulsing were not significant as seen in Fig. 5. The sensitivities predicted for pulsed heavy ions are much less for pulsed magnetic fusion neutrons. Point defect concentrations and hence pulsed effects are much less for neutron irradiation than for heavy ion irradiation.

Calculated void nucleation rates were suppressed by pulsing when significant annealing of subcritical voids occured in the interpulse period.[8,9] The theoretical predictions of void nucleation, however, have not been confirmed experimentally.

Pulsed flux effects on phase stability can cause significant changes in swelling behavior. Therefore, swelling in alloys that are unstable during irradiation may be strongly affected by pulsing.

Pulsed heavy ion and electron irradiations have demonstrated that details of void microstructures can be affected by pulse/anneal cycles. A collective examination of the data, however, does not reveal consistent trends to adopt for pulsed magnetic fusion predictions. Irradiation and material conditions, including the presence of helium, affected pulsed behavior in contrasting ways. Although details of the microstructure were altered by pulsing, the net effect on observed swelling was not large in most cases (but not all, e.g., Fig. 6).

4.2.2 Radiation Hardening

When instantaneous displacement rates are high (ICF), fast defect clustering may cause significant rates of radiation induced hardening that may contribute to loss of ductility in austenitic steels and increase the ductile-to-brittle transition temperature (DBTT) in ferritic steels. For example, the increase in DBTT caused by defect clusters was predicted to be 50 to 100 K for steady irradiation of ferritic steel at room temperature and to a fluence of about 10^{23} n/m^2.[31] The predicted enhancement in defect clustering shown in Fig. 2 suggests that pulsing should strongly influence clustering and hence embrittlement of ferritics at low temperature and low doses.

4.2.3 Irradiation Creep

Pulsed flux effects on irradiation creep derive from modified effective damage rates and from phase instability. Pulsed effects on cyclic climb and enhanced climb glide creep rates were not predicted to be significant for fusion reactor irradiation and microstructural conditions. Alloys that derive their creep resistance from solid solution and precipiate strengthening could be strongly influenced by pulsed effects on phase stability.

4.2.4 Phase Stability

Pulsed effects on the type and distribution of precipitates can affect the radiation sensitivity of alloys. Consequently, the mechanical and physical properties that depend on solutes and precipitates can be affected. Pulsed irradiation compared to steady irradiation is expected to increase the quantity of thermally stable phases and decrease the quantity of irradiation induced phases and to a lesser extent irradiation enhanced phases. Pulse irradiation displaces the alloy away from equilibrium states, whereas pulse annealing allows recovery of the displaced state to the equilibrium state. The competition between irradiation induced displacement and annealing induced recovery dictates the details of pulsed irradiation compared to steady irradiation influences.

5. CONCLUSIONS

Theoretical and experimental evaluations of pulsed flux effects on radiation damage indicate that pulse compression for ICF and phase stability for magnetic fusion are important pulsed effects issues. Pulse compression, i.e., brief periods of high damage rate, increased mutual recombination of point defects and increased the interstitial clustering kinetics. On the other hand, pulse annealing periods allowed recovery of nonequilibrium defect states, irradiation microstructures and radiation modified phase changes. Pulsed irradiation compared to steady irradiation experiments conducted at constant instantaneous damage rates have shown significant differences in irradiation response for alloys containing unstable phases. Stable alloys were generally insensitive to pulsed flux effects except at high temperature. Pulsing theories have shown that greater pulsing effects are expected for heavy ion irradiation damage rates than for magnetic fusion damage rates, and for low dose microstructures than for high dose microstructures.

ACKNOWLEDGEMENT

This work was supported by the Division of Materials Sciences, Office of Basis Energy Sciences of the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 with Battelle Memorial Institute and under Contract W-7405-eng-26 with the Union Carbide Corporation and by the Office of Fusion Energy of the U.S. Department of Energy.

REFERENCES

1. N.M. Ghoniem and G.L. Kulcinski, Nuclear Technology/Fusion Volume 2, Number 2 (1982) 165.

2. E.H. Lee, N.H. Packan and L.K. Mansur, J. Nucl. Mater. 117 (1983) 123.

3. J.A. Sprague and F.A. Smidt, Jr., NRL Memorandum Report 2629, Naval Research Laboratory (1973).

4. A. Taylor et al., ANL/CTR/TM-39, Argonne National Laboratory (1975).

5. J.L. Brimhall, E.P. Simonen, and L.A. Charlot, J. Nucl. Mater. 117 (1983) 118.

6. K. Miyahara, N.H. Packan, and N. Igata, The effect of pulse irradiation on void swelling of a 'pure' 316 stainless steel, in: Effect of Radiation on Materials: Eleventh Conference, ASTM STP 782, eds., H.R. Brager and J.S. Perrin (American Society for Testing and Materials, 1982) pp. 941-952.

7. N.M. Ghoniem, J. Nucl. Mater. 89, No. 2 and 3 (1980) 359.

8. G.R. Odette and R. Myers, CTR Quarterly Progress Report, HEDL TME/7590 (Apr-June 1975) 2.

9. Y.H. Choi, A.L. Bement, and K.C. Russell, Proc. Conf. Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, 1975, CONF-750989, eds., J.S. Watson and F.W. Wiffen, U.S. Department of Commerce (1976) p. II-1.

10. E.P. Simonen, J. Nucl. Mater. 117 (1983) 113.

11. N.H. Ghoniem and G.L. Kulcinski, Nucl. Eng. Des. 52, 1 (1979) 111.

12. E.P. Simonen, J. Nucl. Mater. 90 (1980) 282.

13. E.P. Simonen and C.H. Henager, Jr., J. Nucl. Mater. 103 and 104 (1981) 1281.

14. H. Gurol and N.M. Ghoniem, Rad. Eff. 52 (1980) 103.

15. H. Gurol, N.M. Ghoniem and W.G. Wolfer, J. Nucl. Mater. 103 and 104 (1981) 1251.

16. H. Gurol, N. Ghoniem, and W. Wolfer, J. Nucl. Mater. 99 (1981) 1.

17. Nghi Q. Lam., G. Leaf, and R.A. Johnson, J. Nucl. Mater. 74 (1978) 277.

18. R. Sizmann, J. Nucl. Mater. 69 and 70 (1978) 386.

19. C. Abromeit and R. Poerschke, J. Nucl. Mater. 82 (1979) 298.

20. W.G. Wolfer, L.K. Mansur, and J.A. Sprague, Theory of Swelling and Irradiation Creep, in: Radiation Effects in Breeder Reactor Structural Materials, eds. M.L. Bleiberg and J.W. Bennett (The Metallurgical Society of AIME, New York, 1977) pp. 841-864.

21. N.M. Ghoniem and H. Gurol, Rad. Eff. 55 (1981) 209.

22. E.P. Simonen, Theory of Depleted Zone Annealing During Pulsed Irradiation, this volume.

23. L.K. Mansur, W.A. Coghlan, T.C. Reiley and W.G. Wolfer, J. Nucl. Mater. 103 and 104 (1981) 1257.

24. A. Taylor, D.I. Potter, and H. Wiedersich, ANL/FPP-79-3, Argonne National Laboratory (1979).

25. J.L. Brimhall, E.P. Simonen, and L.A. Charlot, Pulsed Ion Irradiated Microstructures in Molybdenum, this volume.

26. J.L. Brimhall and B. Mastel, Rad. Eff. 3 (1970) 203.

27. R.W. Powell and G.R. Odette, J. Nucl. Mater. 85 and 86 (1979) 695.

28. N.H. Packan, J. Nucl. Mater. 103 and 104 (1981) 1029.

29. N.H. Packan, Temperature aspects of pulsed ion bombardment in an austenitic alloy, this volume.

30. A. Hishinuma, N.H. Packan, E.H. Lee, and L.K. Mansur, Effects of pulsed and/or dual ion irradiation on microstructural evolution in Ti- and Si-modified austenitic alloys, this volume.

31. N.M. Ghoniem, J.N. Alhajji, and F.A. Garner, Hardening of Irradiated Alloys Due to the Simultaneous Formation of Vacancy and Interstitial Loops, in: Eff. of Rad. on Mater: 11th Conf. ASTM STP 782, eds., H.R. Brager and J.S. Perrin (1982) pp. 1054-1072.