ION BOMBARDMENT EFFECTS ON THE FATIGUE LIFE OF STAINLESS STEEL UNDER SIMULATED FUSION FIRST WALL CONDITIONS

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Pressurized tube specimens have been exposed to simultaneous multi-energy surface ion bombardment, fast neutron irradiation and stress and temperature cycling, in a simulation of a possible fusion reactor first wall environment. After ion bombardments equivalent to months-years of reactor operation and up to 30,000 cycles, no detrimental effects on post-irradiation fatigue life were found. The ion damage is found to enhance surface cracking, but this effect is limited to the several micron surface layer in which the ions are implanted.

1. INTRODUCTION

An experiment which simulates several of the components of a possible Tokamak reactor first wall environment - multi-energy ion bombardment, neutron irradiation and stress and temperature cycling - has been performed at the Massachusetts Institute of Technology Research Reactor (MITR-II). Experimental details have been published previously,^{1,2} as have the results of microscopic analysis³ and post-irradiation fatigue testing⁴ of some simulation samples. This paper presents such results for samples which have become available since the last publication, and which have been exposed to higher ion and neutron fluences and greater numbers of stress/temperature cycles. Data from all the samples tested in the simulation experiment is summarized and conclusions based on this data are discussed.

2. EXPERIMENTAL

As mentioned above, detailed descriptions of the experiment are available elsewhere. Very briefly, the simulation is achieved by irradiating sealed, nuclear grade 316 SS pressure capsules in an in-core thimble at the MITR-II in the presence of a thin film of boron enriched to ~96% ^{10}B . (See Figure 1.) The thermal neutron reaction $^{10}\text{B}(n,\alpha)^7\text{Li}$ produces surface ion bombardment by He (maximum penetration ~2.5 μm)

FIGURE 1
Cross-section of the in-core irradiation experiment showing one pressurized tube sample.

and Li (maximum penetration ~1.0 μm) ions. Due to the film thickness and the film/sample geometry, the ions have a broad distribution in both energy and angle of incidence. Some fast neutron irradiation of the pressure capsules also occurs, although the bulk damage production rate is low with respect to the rate of surface damage production by the ion bombardment. Temperature cycling is achieved by

*This research has been sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC02-78-ET52027.

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TABLE 1

Sample irradiation conditions - each row represents one pressurized tube specimen, irradiated in rigs of two. (Pre-irradiation yield stress at 600°C = 305 MPa.)

RIG/SAMPLE	IN-REACTOR CYCLING CONDITIONS			IRRADIATION	
	Maximum stress cycle (MPa)	Temperature (°C)	Number	Neutron fluence (n/m ² , E ≥ 0.1 MeV)	Ion fluence (He + Li/m ²)
1/1	210-295	350-600	16,000	4x10 ²⁴	
1/2	leaked	340-580	16,000	4x10 ²⁴	
2/1	leaked	350-600	14,000	4x10 ²⁴	5x10 ²²
2/2	207-288	340-580	14,000	4x10 ²⁴	5x10 ²²
3/1	210-295	350-600	30,000	8x10 ²⁴	
3/2	207-288	340-580	30,000	8x10 ²⁴	1x10 ²³
4/1	210-295	350-600	28,000	8x10 ²⁴	
4/2	207-288	340-580	28,000	8x10 ²⁴	1x10 ²³

varying the cover gas pressure in the thimble, thus varying the cooling rate of the samples which are continuously heated by the gamma ray flux. Since the specimens are sealed, temperature cycling produces an internal pressure cycle which in turn results in cyclic stresses in the capsule walls. Variable wall thickness allows a range of stresses to be investigated in a single capsule. Table 1 gives the irradiation conditions for all samples tested.

The samples are examined at intervals by optical microscopy and measured using an optical comparator. When irradiation is completed the samples are dissected into rings to allow observation by SEM. Inner and outer ring surfaces are examined and the ring cross-sections are polished and etched to allow observation of sample microstructure and the intersection of ion-bombarded with non-ion-bombarded zones. The final step in sample analysis is to perform fatigue tests on segments of the sample rings. As described in Reference 4, the goal of this test is to determine the effect (if any) of observed surface cracks on fatigue life. The geometry of the test produces maximum tensile stress at the outer surface of the ring, and load levels are chosen to test all sample segments at identical maximum stress of ~130% of the yield stress. This stress level should be sufficiently low to avoid masking the effects of existing cracks, while

still resulting in reasonable fatigue lives where statistical variation among identical samples is not severe. The results for ion-bombarded specimens are compared directly to those for specimens having undergone similar in-reactor cycling but without ion bombardment.

3. RESULTS

Due to the unique ion bombardment conditions (a broad range of ion angles and energies) present in this experiment, and their relevance to potential fusion reactor environments, the development of sample surface morphology is of interest. This aspect is discussed in another paper at this conference,⁵ and only those features which are of direct relevance to the mechanical behaviour of the samples are discussed here. Specifically, all samples have shown surface cracking in higher stress regions (i.e. thin wall areas). A typical crack is illustrated in Figure 2 (the appearance is similar in non-ion-bombarded and ion-bombarded cases). Table 2 gives the number density of such cracks for various samples and stress levels. There is evidently some effect of ion bombardment on the formation of these cracks, but it is not a necessary condition. It was noted that longer cracks are more prevalent on non-ion-bombarded specimens, indicating that the ion damage facilitates

FIGURE 2

Typical surface crack on an ion-bombarded specimen after $\sim 5 \times 10^{22}$ ions/m² and 14,000 stress/temperature cycles. Surface cracks on non-ion-bombarded samples have a similar appearance.

initiation of cracks but does not aid their growth. This is consistent with the highly embrittled nature of the ion-damaged surface layer, although the presence of open cracks is somewhat surprising in light of the expected high compressive stress in this layer. It is possible that the cracking occurs in a thin oxidized layer at the sample surface.

From the polished and etched ring cross-sections which were also examined by SEM, differences between ion-bombarded and non-ion-bombarded specimens can also be identified. Figure 3 illustrates some of these differences. In all the ion-bombarded rings observed, a region corresponding approximately to the expected depth of the ion damaged layer is delineated by differences in the etched microstructure, while in non-ion-bombarded rings the grain structure is observable out to the surface/cross-section intersection. Although discontinuities are observed within the ion-damaged layers, they are not found to extend below these layers into the bulk material. Note (comparing Figure 3 c and d) that the surface of the ion-bombarded layer in the lower stress case (3 d) remains relatively intact while that in the higher stress case (3 c) does not. No readily identifiable differences between ion fluences of $\sim 5 \times 10^{22}$ and $\sim 1 \times 10^{23}$ ions/m² were found.

Table 2 gives post-irradiation fatigue data for

FIGURE 3

SEM micrographs illustrating the typical appearance of the polished and etched ring cross-sections at their intersection with the sample surface. a) is a non-ion-bombarded sample; b) has ion fluence of $\sim 1 \times 10^{23}$ ions/m²; c) and d) have ion fluence of $\sim 5 \times 10^{22}$ ions/m², and they compare the effect of high in-reactor cyclic stress (c) and low in-reactor cyclic stress (d). The ion damaged layer is discernible on the ion-bombarded samples.

segments of the sample capsules indicated. Recall that all segments were tested to the same maximum stress and differences in post-irradiation fatigue life should therefore be due to differences in sample conditions arising from the irradiation experiments. A clear and important result is that ion bombardments up to the fluences achieved do not reduce the

TABLE 2

Summary of in-reactor surface cracking data and post-irradiation fatigue life data for various in-reactor cycling conditions

IN-REACTOR CYCLING CONDITIONS			SURFACE CRACKS		POST-IRRADIATION FATIGUE LIFE	
No. of cycles	Stress range (MPa)	Ion fluence (ion/m ²)	Avg. density (number/mm ²)		Avg. cycles to failure (x10 ³)	95% confidence interval (x10 ³)
16,000	0	0	-	-	115	103-290
16,000	115-160	0	-	-	105	90-121
16,000	145-200	0	-	-	120	94-53
16,000	210-290	0	15	-	-	-
29,000	0	0	-	-	-	-
29,000	115-160	0	-	-	107	94-122
29,000	145-200	0	<5	-	99	87-112
29,000	210-290	0	58	-	91	74-112
14,000	0	5x10 ²²	-	-	320	273-375
14,000	115-160	5x10 ²²	-	-	276	223-340
14,000	145-200	5x10 ²²	15	-	128	97-169
14,000	210-290	5x10 ²²	60	-	114	72-182
29,000	0	1x10 ²³	-	-	-	-
29,000	115-160	1x10 ²³	-	-	282	240-331
29,000	145-200	1x10 ²³	38	-	106	85-131
29,000	210-290	1x10 ²³	103	-	103	75-142

post-irradiation fatigue life. In fact, ion bombardment at low in-reactor stress (cycling to less than half the yield stress) increased the post-irradiation fatigue life compared to non-ion-bombarded samples. This is illustrated in Figure 4. A possible mechanism for this increase is residual compressive stresses in the bombarded layer. (See references 6 and 7 for other examples of this phenomenon.) This is consistent with the microscopy reported above, in that an ion-bombarded layer has been observed to maintain coherence with the bulk material. Furthermore, surface cracking observed on the higher stress specimens supports the additional hypothesis that loss of the integrity of this layer results in a negation of the post-irradiation fatigue life enhancement effect through relief of the compressive stresses.

4. SUMMARY AND CONCLUSIONS

Pressurized tube specimens of reactor grade 316SS have been exposed to simultaneous multi-energy surface ion bombardment, fast neutron irradiation and stress and temperature cycling, in a simulation of a possible fusion reactor first wall environment. Experiments have now been completed which produce ion

FIGURE 4

Simplified comparison of average post-irradiation fatigue life for ion-bombarded specimens subjected to low (less than ~50% of yield stress) stress during in-reactor testing, ion-bombarded specimens subjected to high (between 50 and 95% of yield stress) stress during in-reactor testing, and non-ion-bombarded specimens subjected to low and high stress during in-reactor testing.

bombardments equivalent to fusion reactor operating times of up to several years. Although such bombardments have been found to enhance the formation of short surface cracks, these cracks do not penetrate below the ion-damaged surface layer (several microns in depth). Post-irradiation fatigue testing reveals no detrimental effect of ion bombardment on fatigue life. Where a coherent surface layer is maintained, ion bombardment has even been found to increase post-irradiation fatigue life.

ACKNOWLEDGEMENTS

Mr. H. Andresen was a major contributor to the conception, design and operation of this experiment, and his work is gratefully acknowledged. We would also like to thank Profs. I.W. Chen, A.S. Argon, N.J. Grant, R.M.N. Pelloux and A.W. Nelson of M.I.T. for helpful consultation. Mr. S.G. DiPietro contributed extensive technical assistance. The Hahn Meitner Institute and the Government of Canada provided financial support.

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