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IRRADIATION BEHAVIOR OF BONDED STRUCTURES: IMPACT OF SWELLING-CREEP-STRESS RELATIONSHIP

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ABSTRACT

Radiation damage will be a major key point in the design of the many duplex components in fusion reactors. There is a substantial amount of available data showing that stress plays a major role in the onset, and possibly the rate, of void growth in austenitic stainless steels. There is also a strong support for models which predict a coupling of swelling and creep through the stress environment. A parametric study for the stress-enhanced swelling and its connection to creep is conducted for a typical fusion power demonstration reactor.

I. INTRODUCTION

Duplex structures (i.e., coatings or thin films on a substrate structure) are likely to be used in both near-term and commercial fusion reactors. The bonding of these structures leads to complicated stress fields which must be understood in order to evaluate the probability of failure for the device.[1] Radiation damage will be a major factor in the design of the different duplex components and the synergistic effects of high heat fluxes, high dpa (displacement per atom) levels, and high primary stresses must be taken into consideration. While radiation-effects data on (as well as modelling for) fundamental phenomena can be correlated to structural effects, the uncertainty in the synergistic effects could jeopardize the success of the final design.[2]

The mechanisms of irradiation damage at the interface of bonded structures are not well understood although the damage mechanisms present in metallic materials should also apply to the damage in coatings (e.g., swelling or differential swelling). The properties of greatest concern are the fatigue/crack propagation properties and the effects of irradiation on swelling and embrittlement of the materials.[3]

Swelling due to radiation-induced voids is a major concern for the first wall of fusion devices at temperatures of 400°C and above, and has been the focus of considerable alloy development effort since 1970's.[4] Stress is also known to reduce the incubation period for swelling (see Section II). Since one probable mechanism of failure of bonded structures is, in fact, the level of differential swelling,[5] it is obvious why an understanding of swelling (and the effect of stress on it) is critical to the design of successful duplex structures.

Since irradiation creep and swelling have a common source, an interrelationship between both phenomena exists.[6] There would be many practical consequences of such coupling. Flinn et al.[7] indicated that if no competing mechanism existed (swelling-enhanced creep for example), the residual stresses due to differential swelling could build up with exposure to a level where a component could yield or fracture. Thus, if irradiation creep and swelling are proportional to each other, many of the problems generated by differential swelling would be minimized through the relaxation mechanism of the swelling-enhanced creep. Daenner and Raeder[8] indicated that it would be dangerous to regard swelling and creep separately. They also proved that it is dangerous to see the stress/strain analysis isolated from the materials behavior. Figure 1 is a schematic of the interrelationships that exist between swelling, creep, and stress. The heavy lines indicate the areas that are examined in this paper.

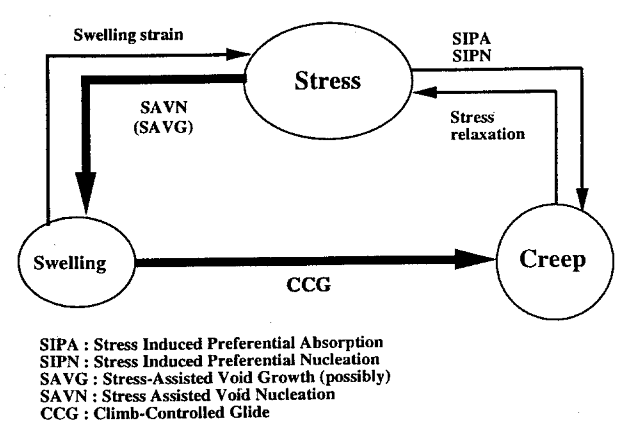

Fig. 1. Relationship between Swelling-Creep-Stress in a radiation environment.

For ITER and beyond, experimental data on the effect of stress on swelling, and the relationship between radiation creep and swelling are badly needed.[9] For example, one of the major concerns for 316 SS is the differential swelling in the 400-500°C range.[10] This is the range where stress-enhanced swelling is an important factor. While extensive stress analyses have been carried out for high heat flux structures made of single materials such as 316 stainless steel, stress analysis for duplex structures is only in its early stages of development.[11] The major work in this area is mainly from Mattas,[9,12,13] Glasgow,[14] and Blanchard.[1,15] None of these previous works, as well as the few inelastic stress analyses that included radiation effects, had incorporated the effect of stress on the swelling behavior of the structure. As for the interrelationship between creep and swelling, only Mattas[9] took it into consideration.

II. STRESS-ENHANCED SWELLING

The effect of stress on swelling was first recognized in 1967 when Cawthorne and Fulton[16] reported that "there is no doubt that stress and strain during irradiation will influence void growth." Since that time, the available data shows that stress plays a major role in the onset (and possibly) the rate of void growth in AISI 316 stainless steel in a variety of metallurgical conditions.[7,16,25] A more limited set of data on AISI 304[26] as well as nickel[27−31] shows that the effect of stress on void swelling is not limited only to the 316 stainless steel. A complete survey of the available data is presented in Ref. 32.

III. MODELLING OF STRESS-ENHANCED SWELLING

An empirical constitutive equation for the stress effect on swelling incubation dose is given as the larger of[33]

$$\tau_e = \tau - q(T)\,\sigma_h \qquad (1)$$

$$\tau_e = 0.5\,. \qquad (2)$$

τ_e is the incubation parameter in units of 10^{22} n $\cdot$ cm^{-2} ($E >$ 0.1 MeV), where $q(T)$ expressed in the units of 10^{22} n $\cdot$ cm$^{-2}\cdot$ MPa^{-1} is calculated[33] from

$$q(T) = q_0 + \exp[a - Q'/(T + 273]\,. \qquad (3)$$

T is the temperature in units of °C,
σ_h is the hydrostatic stress in units of MPa,

$$\sigma_h = \frac{1}{3}(|\sigma_x| + |\sigma_y| + |\sigma_z|),$$

where $q_0 = 0.013$, $a = 51.4$, $Q' = 50,000$ in units of °C^{-1}. Based on the observation that the compressive as well as tensile stresses enhance swelling,[25,34−37] the absolute values of the stresses are used in the calculation of the hydrostatic stress. The modified incubation dose is then used in conjunction with the swelling equation for 316 SS developed for the fuel pin cladding in fast reactors.[38]

Straightforward use of the stress effect on incubation dose in fusion designs is complicated by the presence of time-varying stress histories. A formalism, the Incubation Averaged Fluence (IAF) technique,[19] has been developed so that the time-dependent stress can be included in calculations of the stress effect on incubation dose.

The IAF, $f(t)$, is defined as[19]

$$f(t) = \int_0^t \frac{\phi(t')}{\tau_e(t')}\,dt'\,. \qquad (4)$$

In this equation the effective incubation fluence τ_e depends on time through the time variation of the hydrostatic stress σ_H. The value of σ_H is used to calculate τ_e from equations (1) or (2). The condition for swelling to remain in the incubation phase is now $f(t) < 1$, while the condition for steady state swelling is $f(t) > 1$.

IV. COUPLING BETWEEN IRRADIATION CREEP AND SWELLING

In a number of recent reports the creep-swelling relationship has been investigated for annealed AISI 304L[54,55] and various thermomechanical treatments of AISI 316 stainless steel.[39−45] These studies were conducted in EBR-II and showed a remarkable consistency in results. It was found that that at most temperatures of interest, irradiation creep could be described as a combination of several minor contributions and two major contributions.[46] The major contributions were associated with the creep compliance, a quantity unrelated to void swelling, and a swelling-driven creep component. Other similar studies have also been conducted on the Prime Candidate Alloy (PCA) in FFTF[47] and for the ferritic/martensitic alloys HT9 and 9Cr1Mo [65] which showed the same trend. It has been proposed[46−50] that the creep rate at any relevant temperature is linearly dependent on stress and related to the swelling rate by the following relation:

$$\frac{\dot{\epsilon}}{\sigma} = B_0 + D_0\dot{S}\,. \qquad (5)$$

The creep compliance B_0 has been shown to be approximately equal to 10^{-6} MPa^{-1} for a wide range of austenitic steels. The swelling-enhanced creep coefficient D_0 is likewise thought to be relatively constant ≈ 0.01 MPa^{-1} over a wide range of steels and temperatures. This relationship ignores the short transient usually observed in cold-worked alloys.[50] If we accept the proposed insensitivity of B_0 and D_0 to composition and starting microstructure, then the sensitivities of swelling will dominate the creep behavior at high fluence (where, as shown later, the effect of stress on swelling is more pronounced). Note that Equation (5) requires a swelling rate of greater than 0.01%/dpa (which is generally the case) to give dominance to the second term over the first one, i.e., to make the swelling behavior dominant over the irradiation creep behavior.[50] It is clear that due to the stress dependence of swelling, an apparent deviation from the linear stress dependence of the creep should be anticipated at high swelling rates ($> 0.01\%$ per dpa). This was reported for 1.4981 type stainless steel.[49]

Some research indicated that the creep rate in AISI 316 stainless steel declines as swelling approaches levels in excess of 5% for dpa < 50, and at 550°C.[51] It is not yet clear whether the cessation of creep arises as a direct consequence of large swelling levels or whether other late-term microstructural developments are responsible.[51] The increase in the stress-enhanced swelling with temperature as well as the observed cessation of irradiation creep may have deleterious effects on the performance of bonded structures.

V. STRESS ANALYSIS OF BONDED STRUCTURES

The effect of stress history on the development of swelling in bonded structures and the role played by stress-enhanced swelling in irradiation creep calculations has been incorporated into the TSTRESS code[38] in its latest version GTSTRESS.[52] The code uses the method of the boundary integral method formulated for time dependent plastic deformation in one dimension.

Four different sources of stress were initially considered: (1) membrane loads from internal coolant pressures, (2) temperature gradients through the wall caused by steady-state heat fluxes, (3) irradiation induced differential swelling gradients through the wall, and (4) residual stress gradients caused by both thermal and irradiation creep-induced stress relaxation.

The code was modified to incorporate models for the stress-enhanced swelling. The modification of the irradiation creep due to the stress-enhanced swelling was also taken into consideration. The ability of the code to produce the swelling distribution throughout the thickness of the first wall (as well as in its coating) allows for the proper assessment of the swelling behavior especially near the interfacial area between the coating and the substrate. This gives an excellent chance to investigate the impact of differential swelling on the bonding of duplex structures.

VI. RESULTS

The behavior of 20% cold-worked 316 stainless steel plate free to expand but not to bend (an ideal simulation for first wall structures) and subject to different irradiation, stress, as well as thermal conditions was first investigated. The attempt was to determine an envelope for the behavior of the stress-enhanced swelling phenomena, and the impact of the swelling on the irradiation creep. The choice of 316 stainless steel was made since it is the only material on which the effect of stress on swelling has been studied and modeled. The upper temperature (525°C) was chosen since this is the temperature beyond which stress may have an impact on the swelling rate as well as the incubation period. Also, the effect of gas generation would become important above this temperature. Since the impact of stress on swelling is small below 400°C, most calculations were limited to above 400°C. In the following discussion, volumetric swelling is shown for three conditions of interest to the behavior of bonded structures: at the surface, using the average over the first millimeter, and using the average over the whole thickness. Also, in the following results, stress always refers to σ_x. It is apparent from the different results that the stress-enhanced swelling phenomena complicates the prediction of the irradiation behavior of bonded structures and will have a major role on their performance at the interfaces.

A. Parametric Study of the Stress-Enhanced Swelling Phenomena

Effect of plate thickness. Four different thicknesses were used in the calculations; 3, 5, 7, and 9 mm as shown in Fig. 2.

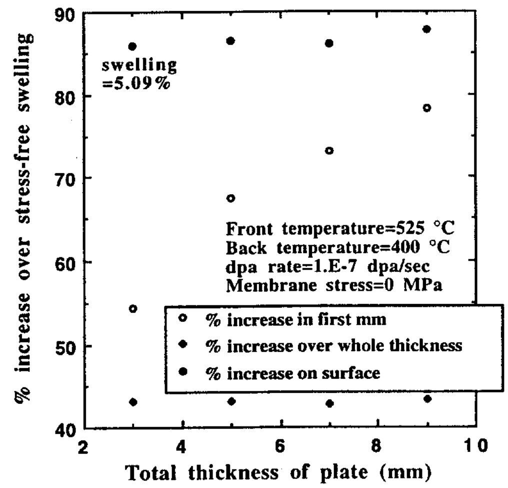

Fig. 2. Effect of plate thickness on the stress-enhanced swelling of 316 SS plate after 31.5 dpa.

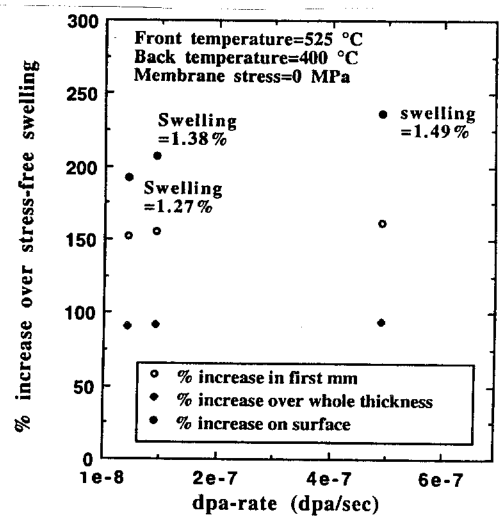

Fig. 3. Effect of dpa rate on the stress-enhanced swelling behavior of 5 mm 316 SS plate after 15.75 dpa.

The same temperature range was maintained (400-525°C). In this case, varying the plate thickness had little effect on surface swelling and the average swelling along the whole thickness. Since the first mm has a different temperature gradient in each case, being hotter for the large thickness, the 9 mm plate experienced the largest increase in swelling.

Effect of damage rate. Three different cases were investigated (5.E-8, 1.E-7, and 5.E-7 dpa/s) at an accumulated dose of 15.75 dpa as shown in Fig. 3. The stress-enhanced phenomena played a major role as the damage rate increases. This has an impact for the DEMO as well as commercial reactors.

Effect of membrane stress. As shown in Fig. 4, the stress-enhanced swelling is decreased with the increase in membrane stress. The trend will be reversed as the stress level increases. This is explained for a simple stress distribution in Fig. 5. As the membrane stress increases, the stress on the surface as well as

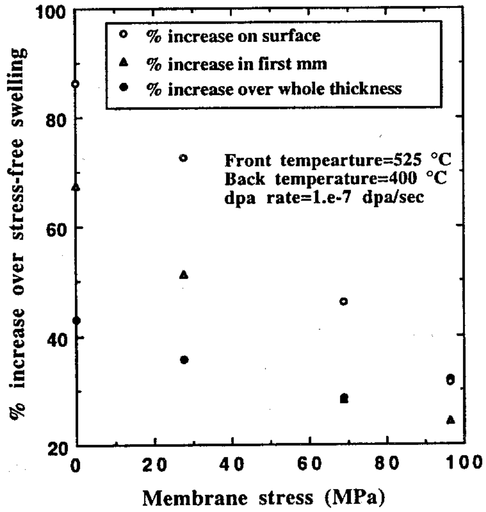

Fig. 4. Effect of membrane stress on the stress-enhanced swelling of a 5 mm 316 SS plate after 31.5 dpa.

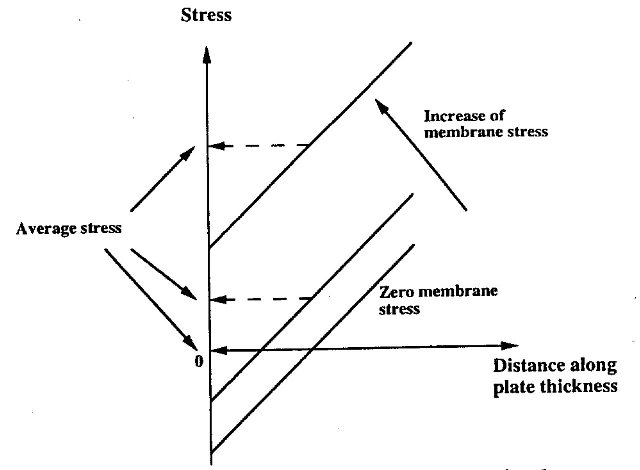

Fig. 5. Stress distribution in a plate subject to simple membrane stress. Initial stress distribution is assumed symetric.

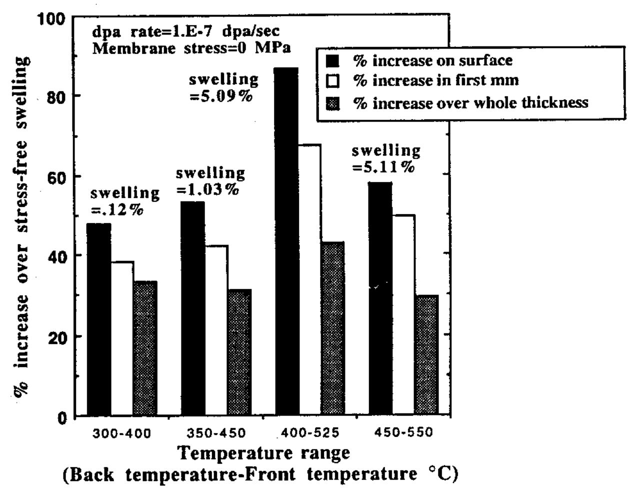

Fig. 6. Effect of temperature range on the stress-enhanced swelling behavior of a 5 mm 316 SS after 31.5 dpa.

in the first millimeter will decrease in value, then it will increase once more, thus increasing the stress-enhanced swelling. We have to keep in mind that what is important is the absolute value of the stress. The importance of the membrane stress effect on swelling should be considered along with the future trends of using high temperature, high pressure coolants that generate high membrane stresses.

Effect of temperature range. As shown in Fig. 6, the impact of the phenomena is high for high temperature ranges. It is important to note that this trend only reflects the increased stress levels rather than the promotion of the stress-enhanced swelling with temperature (in this temperature range, the stress-enhanced phenomena is an athermal process). This is also clear when considering that the reduction in stress-enhanced swelling as the temperature gets higher since the thermal creep began to be effective in reducing stress levels.

Swelling evolution with time. As shown in Fig. 7, the stress-enhanced swelling will have a major role in the beginning of life (regardless of the low swelling value). This is expected since in the beginning, before the creep begins to redistribute the stresses, the stress levels will be high. This will have an impact on the the early performance of bonded structures.

Stress distribution. The time dependence of the stress distribution is shown in Fig. 8. A remarkable deviation from linearity is observed, especially on the surface (i.e., at the coating). To investigate the roots of this behavior, both the swelling and the creep evolution were calculated. It is quite obvious from Fig. 9 that the evolution of stress-enhanced swelling is the key factor behind the resultant stress distribution. This is even more obvious when the stress-enhanced swelling with time is used to enhance the irradiation creep. The stress relaxation due to creep is more effective on the surface as a result of the dominant effect of the stress-enhanced swelling in this area. It is also worth mentioning that, in all the above calculations, the stress level did not exceed the proportional elastic limit of the 20% CW stainless steel. Thus, swelling always increased with stress.

B. Effect of Stress-Swelling-Creep Coupling

As shown in Figs. 10 and 11, the creep-swelling coupling has a major impact on the swelling distribution, as well as on the stress evolution. As a result, the stress-enhanced swelling will be reduced (by as much as 40% in Fig. 10). It is important to note that the creep relaxation of stress on the surface will have an important effect on the generation of intrinsic stresses along the interface if a coating is applied. It is thus obvious that the effect of stress-enhanced swelling should not be taken into design analysis without taking the impact of swelling on creep into consideration. Otherwise, an overestimation of swelling, especially along interfaces, may result. One complication is the cessation of irradiation creep at high values of swelling (5%) that was reported earlier.[39,52]

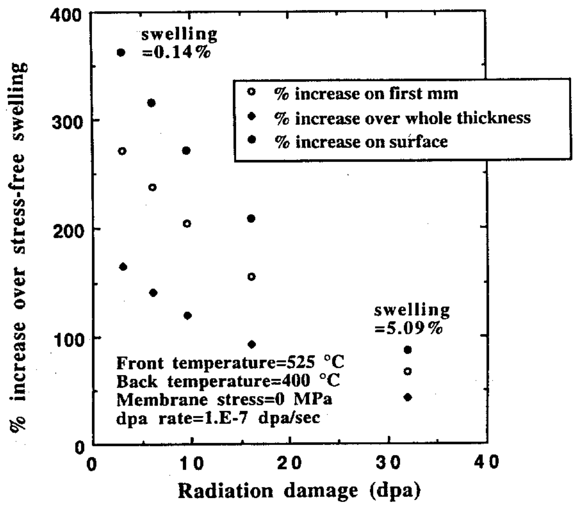

Fig. 7. Effect of stress on swelling behavior of a 5 mm SS plate as a function of radiation dose.

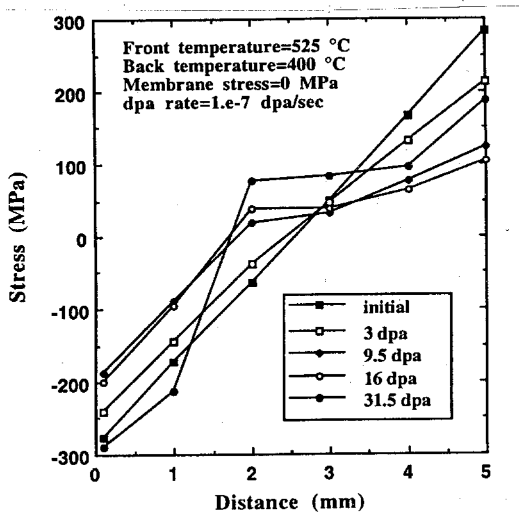

Fig. 8. Evolution of stress as a function of dpa for a 5 mm 316 SS plate.

C. Be/SS Structure for the DEMO Design

To simulate an actual case of a duplex structure that uses stainless steel, the parameters of the first wall of a DEMO reactor were used.[53] These were:

Neutron wall loading	2.1
Thickness of Be (70% TD) tiles	2 mm
Thickness of 20% CW 316 SS	4 mm
Surface temperature	730 K
Interface temperature	725 K
Back temperature	670 K
Coolant temperature	653 K
Membrane load	50 MPa
Lifetime	10 years
Availability	50%
Damage level	84 dpa
Gas generation rate in Be	6405 appm/year

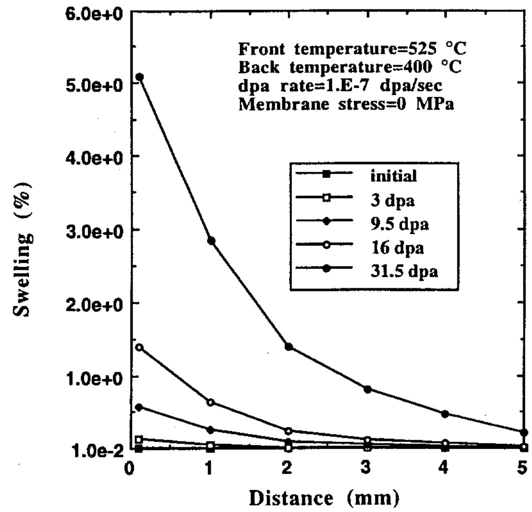

Fig. 9. Evolution of the stress-enhanced swelling distribution as a function of dpa for a 5 mm 316 SS plate.

Since the stress-enhanced swelling phenomena is negligible below 300°C, all the temperatures used above are in fact 100 degrees higher than those in the original design. Recent data for Be[54] were taken into consideration to account for the gas induced swelling as well the irradiation creep. The percentage increase in swelling due to stress is shown in Fig. 12 as a function of thickness. Because of the way stress redistributed in steel, tending to peak at the back end of the substrate, the increase in swelling is more pronounced there, eventually reaching a value of 20% over the stress free value. It should be noted that at the back end of the substrate the low temperature should result in low swelling values. It is obvious that the stress-enhanced swelling increased the swelling level at the back of the substrate more than it affected the swelling level at the interface (as would have been anticipated from results of Section VI). Thus, the im-

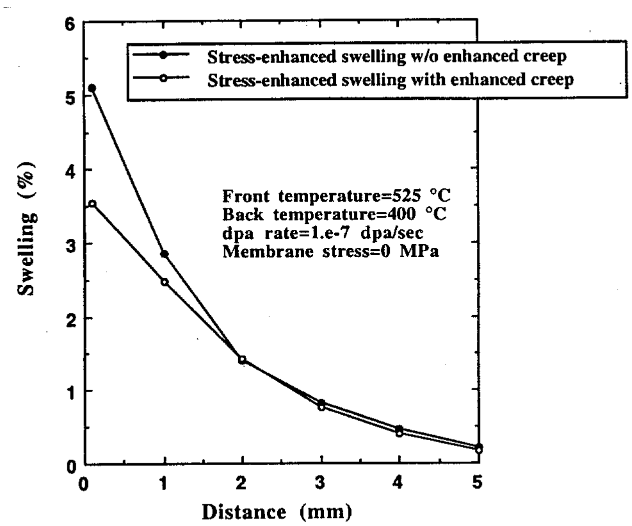

Fig. 10. Effect of (stress-enhanced swelling)-enhanced creep on the swelling of a 5 mm 316 SS plate after 31.5 dpa.

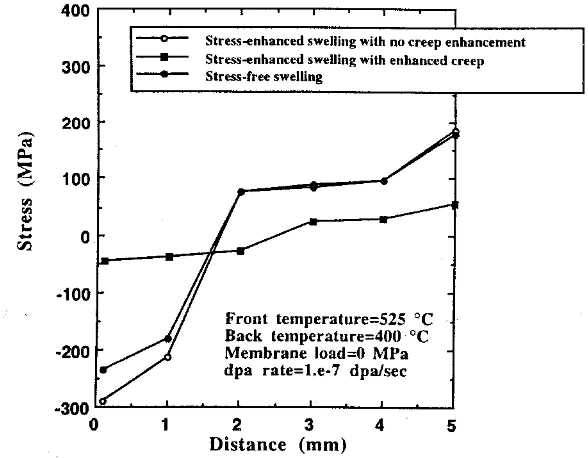

Fig. 11. Effect of stress-enhanced swelling with enhanced creep on the stress distribution in a 5 mm 316 SS plate after 31.5 dpa.

pact of stress-enhanced swelling should be evaluated in the relevant stress environment. Coupling between swelling and creep was not taken into consideration in the last figure to single out the impact of stress-enhanced swelling. It is expected that if this coupling is taken into consideration, the increase in swelling at the back will be reduced since creep will be enhanced more there.

VI. CONCLUSIONS

Radiation damage will be a key point in the design of the different components of fusion reactors but unfortunately, the mechanisms of irradiation damage in bonded structures have not

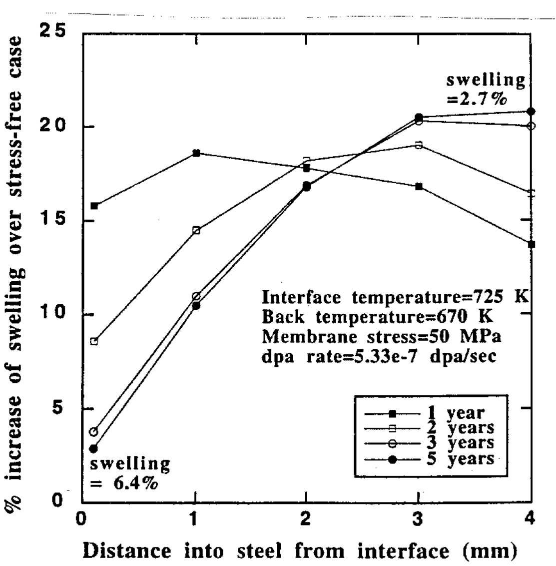

Fig. 12. Percentage increase in stress enhanced swelling over the stress free case for a 20% cw 316 SS substrate coated with 2 mm of Be.

received much attention. The impact of stress on the incubation period for swelling should be taken into consideration for the analysis of both near and far term reactors, especially those experiencing high dose levels and using high temperature coolants and pressures (i.e., high primary stress levels). The interrelationship between (stress-enhanced) swelling and creep is a vital one in the proper assessment of the stress evolution in bonded structures. Failure to incorporate this effect may result in an overestimation of swelling. Whether or not creep ceases at high values of swelling will remain a key point in the assessment.

Many questions concerning the stress-enhanced swelling phenomena are still to be answered. Further experimental, as well as theoretical, work is necessary to assess and model the effect of stress on cavity density, the observed enhanced void growth especially at high temperatures. The role played by the shear component of the stress, as well as the synergistic effects of temperature, damage rate, gas generation rate, and stress still need to be more fully understood before the influence of the different variables relevant to fusion applications can be assessed.

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