Stress-Enhanced Swelling: Mechanisms and Implications for Fusion Reactors

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Abstract

Radiation damage will be a key aspect in the design of the many duplex components in fusion reactors and differential swelling is one of the key elements anticipated to initiate damage in these components. 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 strong support for models which predict a coupling of swelling and creep through the stress environment. Irradiation behavior of bonded structures in fusion reactors is analyzed by taking into consideration these two phenomena in the relevant stress environment.

1. 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 problems 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.

The mechanisms of irradiation damage at the interface of bonded structures are not well understood. 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 [2].

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 the 1970's [3]. Researchers typically used end of life limits on swelling ranges from 2-10% volumetric swelling [4]. There is a substantial amount of available data indicating that stress plays a major role in the onset and rate of void growth in AISI 316 stainless steel in a variety of metallurgical conditions. A more limited set of data on AISI 304 and from a number of other commercial alloys shows that the effect of stress on swelling probably occurs in all alloys subject to swelling (see Section 2.1). A particularly unfortunate feature of this problem is that it is possible to envisage a large number of processes that would produce an interaction between stress and swelling. Since one probable mechanism of failure of bonded structures is, in fact, the level of differential swelling between coating and substrate [5], it is obvious that an understanding of swelling (and the effect of stress on it) is critical to the design of successful duplex structures.

Stresses will arise in restrained components that undergo differential swelling resulting from flux and temperature gradients or from material variables such as the amount of cold-work and alloy composition [6,7]. The differential swelling effect is analogous to thermal stresses caused by differential thermal expansion, but the differential strain mechanism is continuous [8]. In fusion reactors, stresses develop because of the high surface heat flux and irradiation-induced swelling and creep [9]. Also, some tokamak blankets, particularly those using helium as coolant/breeder, may have to operate at relatively high coolant pressures. As a result, the first wall may be subjected to high primary (i.e., load-controlled) stresses in addition to high secondary (i.e., deformation-controlled) stresses such as those associated with gradients or constrained swelling. Adding to the problem of constrained swelling is the massive blanket behind the first wall, which may undergo little or no swelling and provides the necessary constraint to first wall swelling.

Not only does stress have a direct impact on swelling, but it also induces indirect effects. Brailsford and Bullough [10] pointed out that perhaps the environment in which stress-assisted swelling could be most important is in the neighborhood of a crack tip where very high local hydrostatic stresses can occur. Thus the crack propagation analysis can be affected by such behavior. Also, if the application of stress somehow acts to stabilize voids near the grain boundary, the mechanical properties of the irradiated material might be strongly affected [11].

Since irradiation creep and swelling have a common source (i.e., the displacement of atoms by energetic atoms), the possibility of an interrelationship between both phenomena may exist [12]. There would be many practical consequences of such coupling. Flinn et al. [13] 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 [14] indicated that it would be dangerous to regard swelling and creep separately. They also proved that it is dangerous to perform the stress/strain analysis isolated from the materials behavior. It should also be noted that stresses due to enhanced creep will be a source of intrinsic stresses that the designer takes into account.

For ITER and beyond, specific data are desirable concerning the effect of stress on swelling, and the relationship between radiation creep and swelling [15]. It was emphasized that radiation effects should be explicitly considered in any first wall design criteria, and that they need to be included in any lifetime assessment.

2. 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, it became obvious from the substantial amount of available data 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 [13,16-26]. A more limited set of data on AISI 304 [27], Deutsches Institut für Normung DIN 1.4970 and 12RN72 [28] as well as nickel [6,7,29-31] shows that the effect of stress on void swelling is not limited to 316 stainless steel.

Much of the early work on stress-swelling interactions, in the absence of adequate irradiation effects data, involved theoretical modelling. In general, it was predicted that a tensile stress will enhance and a compressive stress will retard the operation of mechanisms associated with the swelling phenomena [32-36]. Most of these predictions were based on the stress effect on dislocation bias for vacancies (see Section 2.2.1). Bates and Gilbert [17] described stress-enhanced swelling in AISI Type 316 stainless steel fuel cladding and showed experimentally that an apparently linear relationship exists between tensile stress and swelling in both annealed and cold-worked material, provided the yield strength of the material is not exceeded. That was confirmed by other investigators who studied the swelling behavior of stressed cladding and compared that with unstressed capsules (see Figure 1) as well as work on pressurized tubes (Figure 2) [16-24,28]. It was later shown that this linear relationship was misleading and that the principal effect of stress was that of shortening the transient regime of swelling [25]. Since the late seventies, the effect of stress has been studied using pressurized tubes (where the stress states were not purely hydrostatic but involved strong shear stresses). Recently, however, irradiated foils were also studied to assess the effect of compressive as well as tensile stress [25,37-40].

2.1 Summary of the stress-enhanced swelling phenomena

The results of stress effects on void swelling are summarized to discriminate between various mechanisms as follows:

1. External stresses reduce the incubation period for void formation [12,25,41-44]. For the case of austenitic steels, this behavior is linear for applied stresses up to the proportional elastic limit of the material. Stresses in excess of the proportional elastic limit can extend the incubation time [17,23,24,44]. Thus, annealed material will show greater sensitivity to stress [45].
2. Both the incubation period and the growth rate are indifferent to reversion of stress from uniaxial tension to compression, indicating a possible effect of deviatoric components of the stress, as well as the hydrostatic component [25,37-40].
3. The total void density established during the nucleation stage may increase [7,42] or decrease [37] with stress. However, as the steady state swelling is reached, the total void density is insensitive to the applied stress [37,46]. Also, the increase in void density is compensated partially by a downward shift of the mean void size, particularly at higher stresses [12].
4. The void growth rate is unaltered by external stresses. The observed increase of void size with increasing stress at a given dose in some experiments is explained as resulting from the reduced incubation time with stress. However, the possibility of stress effects on the growth rate is not totally overruled [40].

Stress-affected swelling spans the entire temperature range applicable to fast reactors, but it appears that more than one mechanism is involved, one which dominates at relatively low temperature and another which controls at higher temperatures (>550°C) [48]. Generally

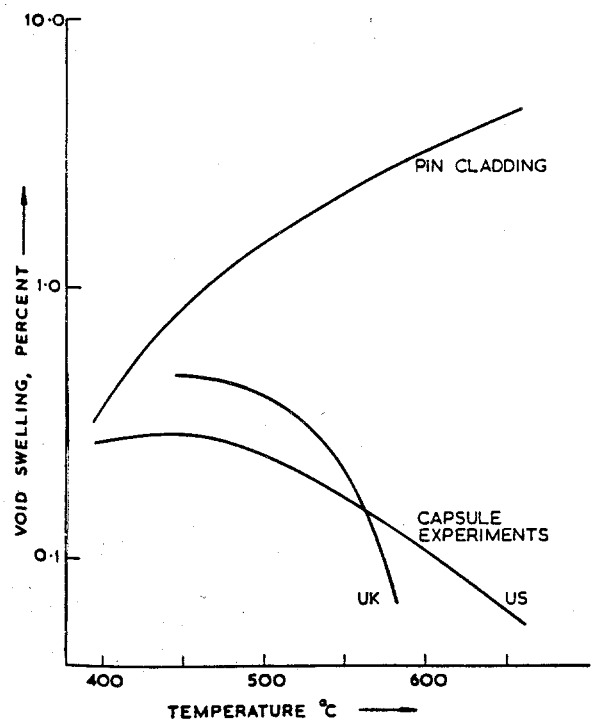

Fig. 1. Swelling-temperature relationships on a SA 316 steel irradiated as cladding and capsule experiments at Dounreay Fast Reactor after 16 dpa [47].

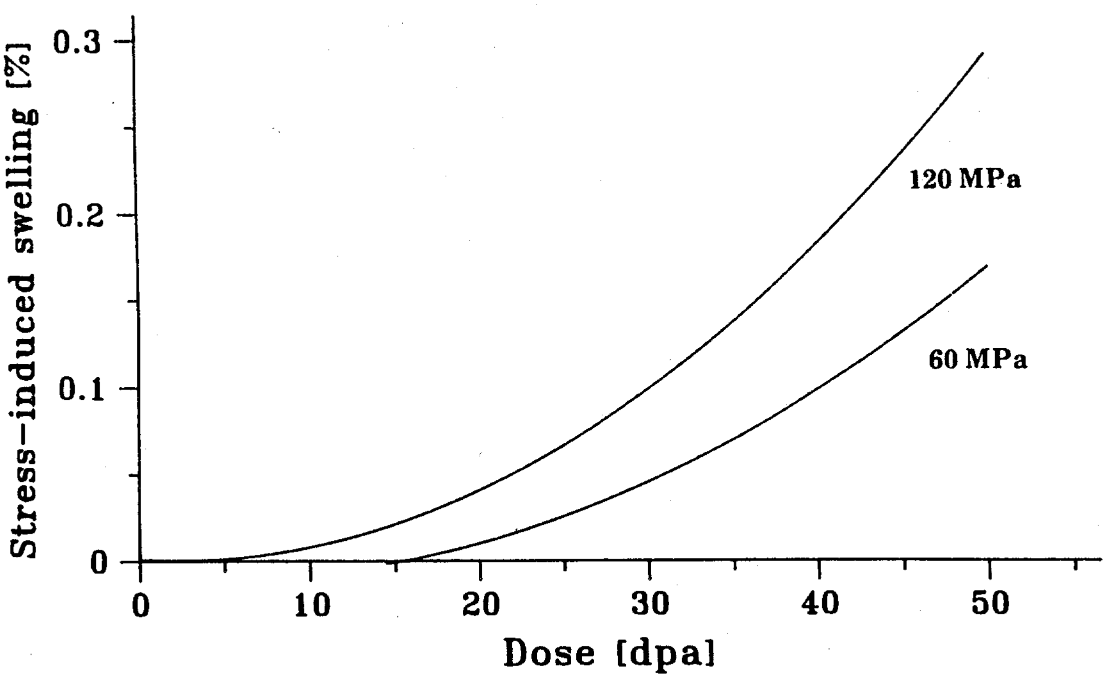

Fig. 2. Reduction of swelling incubation dose due to stress at 420°C for DIN 1.4970 steel after 52 dpa [28].

speaking the effect of stress on void nucleation at temperatures below 400°C may be negligible [48,49]. Thus, it is difficult to observe the phenomena at low temperature [48], particularly in materials with short incubation periods [27]. However, at higher temperatures, the influence of stress is more pronounced [41].

At lower fluences and flux levels, the effect of stress on swelling is difficult to recognize, especially if the temperature is low [27]. It should also be clear that the effect of stress on swelling is a transient one, which is not repeated when the stress is removed, since it affects the incubation dose. Applied stresses probably cannot completely eliminate the incubation period. Porter et al. [27] showed that tensile-shear applied during neutron irradiation cannot shorten the transient duration of AISI 304 below nearly 10 dpa minimum characteristic of the Fe-Cr-Ni and Fe-Cr-Mn systems. The magnitude of the enhanced swelling is very sensitive to dose rate. The action of stress at low irradiation temperatures is more pronounced at the higher displacement rates where void nucleation is more difficult and the transients are longer.

2.2 Stress-enhanced swelling mechanisms

Externally applied stresses do not operate in a mechanical sense directly on the void surface [32]. The microscopic mechanism for the stress enhancement of the swelling rate is that the growth rate for each individual void is the same but a greater number of voids is nucleated when a stress is applied. However, a faster growth rate under stress for each individual void, with the same number of voids as in unstressed material, or a combination of both effects, is not totally overruled. The difference between the two effects is depicted in Figure 3. Since it is possible to envisage a large number of processes that would produce an interaction between stress and swelling, the different mechanisms will be briefly reviewed according to temperature domains.

2.2.1 Low temperature regime

The low temperature regime exhibits a stress effect with little or no temperature dependence [48]. It is important to note that the Q value approach used to describe the reduction of the incubation period with stress (see Section 2.3) is essentially constant at low irradiation temperature but it increases sharply above 600°C as is shown in Fig. 4 [48]. At temperatures below the peak swelling temperature (550°C for 316 SS), the explanation probably is related to the effect of stress on the evolution of dislocation density and the impact that it has on the nucleation period of swelling.

Before discussing the proposed model, it is interesting to note that one of the early models presented to explain the stress-enhanced swelling at low temperatures analyzes the effect of stress on the different capture efficiencies of voids for vacancies and interstitials [6,7,37,43,45,46,50-54]. In this model, as the void grows larger (>100 Å) the shear stress, which is ineffective for small voids, may increase the bias again, thereby reducing the swelling rate. Based on this model, the mechanism is only weakly dependent on temperature [6,7]. Also, a stress effect on void nucleation rates is predicted at all temperatures. If the nucleation rate for the stress-free case is already very large and the incubation period rather short, a further reduction by stress may not be observable [17,54]. Hence, the effect of stress on void nucleation at temperatures below 400°C may be negligible. However, such an effect may be substantial at a temperature of 500°C. Regardless of the success of this model to account for many of the manifestations of the phenomena, it was recently rejected because it predicts lower swelling under compressive hydrostatic stress and this contradicts recent findings [25,37-40].

Since the void nucleation rate depends on the dislocation density, the enhanced nucleation rate may reflect the acceleration of dislocation development with stress. An observable void density is produced in areas where dislocation loop densities were formed in the early stage of irradiation. This indicates the possibility that initial dislocation loops act as the nucleation sites of voids and such a hypothesis was used to formulate a successful model for the stress-enhanced swelling phenomena at low temperatures. The model predicts a shortening of the incubation period for swelling under stress by an accelerated development of the irradiation-induced loop structure [37,38,54]. The origin of this phenomenon may arise from the extraordinarily high strain field near the dislocation loop, thereby strongly enhancing the nucleation of voids [54]. Under stress, the enhanced growth of favorably oriented loops increases the average bias of the system and thus may induce a vacancy supersaturation and promote void nucleation. During

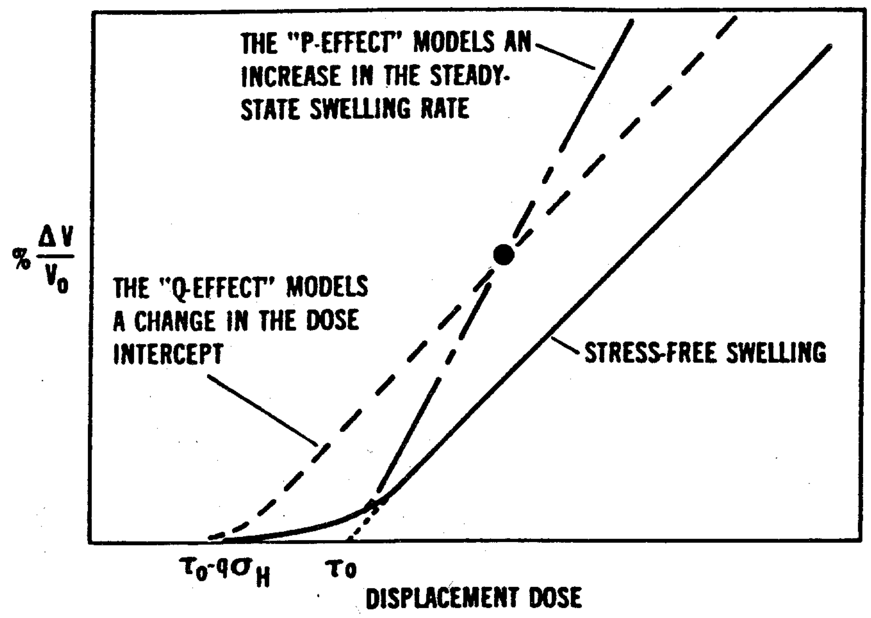

Fig. 3. Schematic representation of the proposed models of stress-enhanced swelling [48].

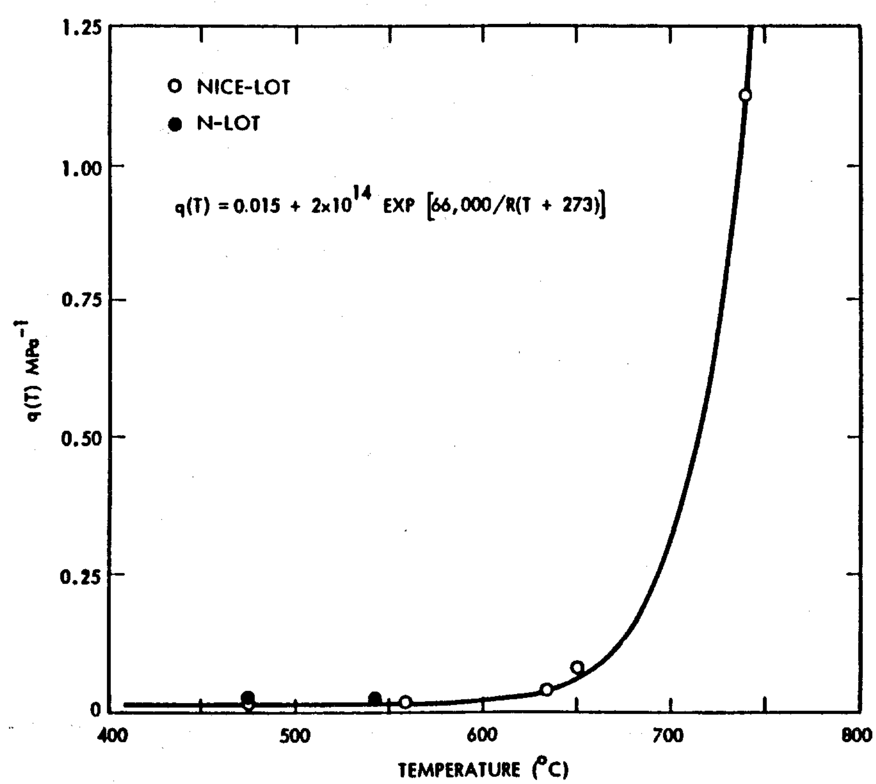

Fig. 4. Temperature and heat dependence of the q-coefficient for 20% CW AISI 316 pressurized tubes irradiated at EBR-II [48].

void growth, the bias of the system is dominated by voids and dislocations, while the effect of stress may become of secondary importance.

This mechanism also depends on the shear component of the external stress and therefore works equally well under tension and compression [48]. It also accounts for the earlier nucleation in the partially annealed alloy reported in the literature when compared to the cold worked material, where the irradiation-induced loops have to compete with the network dislocations in this case [37]. Also, the model exhibits a weak dependence on temperature. As for the extension of the incubation period after the stress reaches its proportional elastic value, it is related to the introduction of additional dislocations (i.e., the plastic yielding of the material) [17,24,44]. Also, if an effect of stress on the steady-state swelling rate exists, it will probably arise due to the increased Frank loop density [49]. It should be noted that the importance of loops as nucleation sites may be dominant if there are no precipitates or other sinks that could act as nucleation sites [54]. Thus, the previous mechanism needs more analysis for materials other than stainless steels.

2.2.2 High temperature regime

Stress may have pronounced effects due to different mechanisms at high irradiation temperatures [55]. The observation of two swelling peaks in unstressed solution-treated 316 steel is consistent with this view that low and high temperature swelling are controlled differently. Also, there are significant changes at around 525°C in the temperature dependencies of void size, void concentration and dislocation density observed at the Dounreay reactor which all may be associated with the change of controlling mechanism (Figs. 5 and 6) [55]. Some of the 550°C data at the highest stresses showed a marked increase in void size and decrease in number density, indicating the possibility that a different, or additional, stress effect exists.

a. Stress enhanced-vacancy thermal re-emission from dislocations

One of the possible effects is the effect of stress on the thermal vacancy concentrations at the various sinks (by altering the free energies of formation). Ultimately this may affect the thermal emission of vacancies from dislocations [35,41,44,46-49,54]. The process is temperature dependent. It was found to be too small at 500°C to account for the sensitivity of the void density to stress. At higher temperatures, however, this mechanism gains in importance. At these temperatures, the thermal supersaturation of vacancies is low and the increment in the supersaturation due to stress can be significant. This would lead to a reduced critical cavity size and hence a reduced incubation time [56].

b. Stress enhanced-vacancy currents to voids

One effect of stress on void growth is expected to be the alteration of the free energies of migration of the point defects, with resultant changes in defect mobility [35,57-59]. In the general triaxial case, the presence of a void leads to a modulation of the local hydrostatic stress over the void surface with deviations above and below the level of hydrostatic stress present in the undisturbed matrix. This modulation then leads to altered point-defect diffusivities and currents and generates nonuniform concentration gradients and fluxes across the void surface. Void growth within grains can thus be enhanced due to stress-motivated point-defect currents. It is important to note that the biased flow of interstitials to voids (due to the stress gradients generated around voids by the external stress) is negligible [35,59]. There is a sharp dependence on temperature because the temperature dependence of the defect diffusivities dominates the temperature behavior (normally, at temperatures above 0.3 T_m all the single radiation-produced point defects (vacancies and interstitials) are mobile [55]). The diffusivities contain exponential terms in temperature, the effect of which overshadows that of other effects.

c. Stress assisted void nucleation-microchemical mechanism

The possibility exists that the required mechanism for stress enhanced swelling (at least in the case of AISI steels) is microchemical in nature [41,42]. However, this does not preclude the possibility that the previously proposed microstructural mechanisms are also operating but not dominant under certain conditions. A plausible explanation of the stress effect [42] is that the degree of microchemical segregation required for swelling to commence is merely decreased by the application of a volumetric stress or the associated application of strain energy to the system. Such an effect may be manifested in a reduction in the effective stacking fault energy for

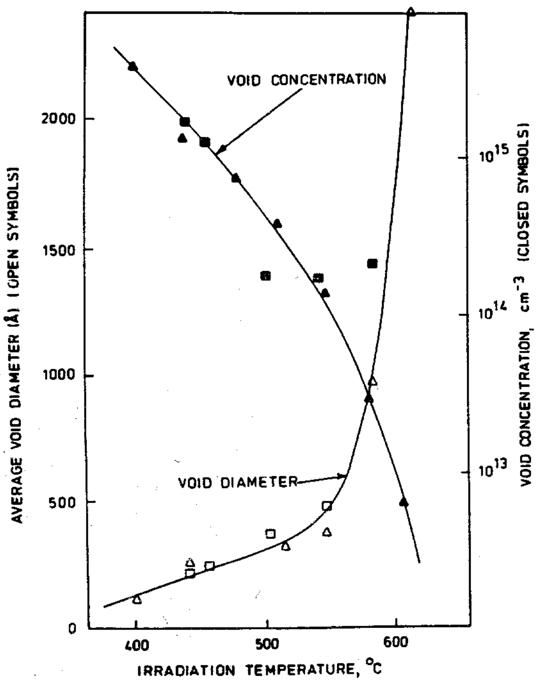

Fig. 5. Average void diameters and void concentration in cold-worked M316 fuel pin cladding at Dounreay reactor for two different burnups [55].

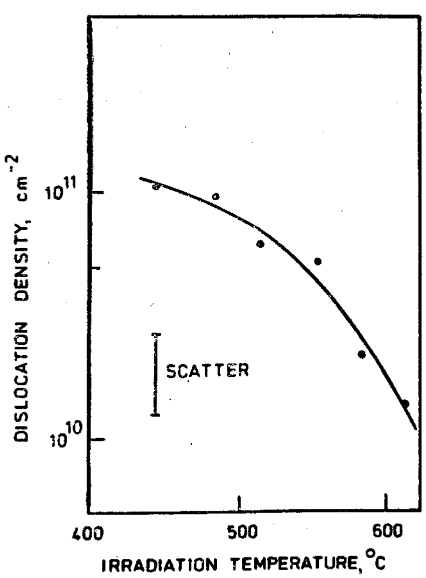

Fig. 6. Dislocation density in V1294 cold-worked M316 cladding at Dounreay reactor [55].

dislocation loops or increases in defect mobilities. This microchemical mechanism is not anticipated to respond to compressive or cyclic stresses in the same manner as would the microstructurally-based mechanisms. As long as experimental constraints prevent a detailed study of phase evolution during low dose irradiation, the importance of this mechanism cannot be identified.

d. Effect of helium generation

Above 525°C the gas generation rate becomes important for swelling of steels [55]. It is only in this higher temperature regime that stress effects would be expected to become significant [55]. However, at these temperatures, stress may act only synergistically [54]. If the gases are produced during irradiation, stresses will then reduce the amount of gas needed to initiate void formation. If the gas is already present at the start of the irradiation, stresses may no longer influence the incubation dose. It is also to be noted that at high doses, gas-driven swelling rates may also exceed bias-driven swelling rates at low doses [47] which supplement the conclusion of an effect of gas generation on the stress-enhanced swelling phenomena. This effect should be understood in the context that the effect of He/dpa ratio on stress-free swelling is non-monotonic and the incubation period could actually be a minimum for helium generation rates characteristic of fusion [60].

e. Other mechanisms

Other mechanisms have also been proposed throughout the literature to explain the stress-enhanced swelling phenomena. It was proposed that tensile stress promotes void growth by opposing the surface tension forces tending to minimize void size [20]. It was proven that the stress must be high (on the order of 370 MPa) and the void diameter large (>200 Å) if stress is to exert a significant effect on void growth. Only at high temperatures, where void diameters are high, should stress then significantly accelerate void development. Thus, this mechanism should be thoroughly investigated especially in the context of the expected high stress fields as well as high dose levels in fusion reactors.

It is also very possible that enhanced irradiation creep under high temperature conditions promotes a coalescence of some of the smaller voids, thus accounting for the observed increase in void size in some experiments [42]. This may prove to be the case, taking into consideration the effect of stress on the void shape. In one study [61], this was taken into consideration by assuming that voids have an ellipsoidal shape. The change in equilibrium shape is negligible for small voids and small stresses; however, as larger voids (i.e., higher temperatures) and higher stresses are considered, the ellipticity ratio for equilibrium increases, eventually leading to spontaneous collapse of the void at a rate determined by the diffusion mechanism (dominant at high temperatures).

It is interesting to note that the growth of grain boundary cavities or helium bubbles under stress was considered in the early stages of the investigations to be the mechanism for the stress-enhanced swelling [32,34]. However, it was concluded that at typical LMFBR operating temperatures, the mechanism is not expected to yield significant density changes since intergranular failure will occur before significant density changes occur due to growth of grain boundary bubbles [32,34].

2.3 Modelling of stress-enhanced swelling

Bates and Gilbert [17], based on experimental data, developed the relationship between stress and swelling for annealed steel of the form (Fig. 7):

$$S_T = S_\circ \left[1 + P\,(\sigma - \beta \ln \sigma/\sigma_p) + \beta \left(\frac{1}{\sigma} - \frac{1}{\sigma_p}\right) \right] \qquad (1)$$

where;

S_T is the total swelling, $S_\circ$ is the stress-free swelling, P is a coefficient (apparently independent of fluence), σ_p is the stress at maximum swelling, and β is another coefficient. The above equation should be used only for stresses less than the unirradiated value of the proportional elastic limit.

Harbourne [8] developed an empirical model for the effect of stress on cladding swelling deduced from the experimental data. This was put in the form

$$\ln (\Delta V / V) = A + (n_0 + K \bar{\sigma}) \ \ln (\phi t) \tag{2}$$

where K is a constant, which may be determined from the experimental data. The values of K obtained in the study were fitted to an Arrhenius temperature function over the range 480 to 670°C. This equation is a modification of the stress-free swelling equation [8].

Brager et al. [12,46] formulated the effect of stress on void nucleation as:

$$\rho_v(\sigma_H) / \rho_v(0) \approx \exp (n \, \Omega \, \sigma_H / kT) \tag{3}$$

where ρ_v is the void number density, n is the number of vacancies in the critical nucleus, Ω is the atomic volume, and σ_H is the hydrostatic stress. The sign convention employed here implies that the application of a tensile stress enhances the probability of void nucleation.

Another equation was formulated [17,23,24,62] for the linear part of solution annealed steel and for the entire range of cold-worked steels:

$$S/S_0 = 1 + P\sigma_{hyd} \tag{4}$$

where σ_{hyd} =hydrostatic stress = $\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$; S = total swelling (%); S_0 = stress-free swelling (%); and P = a constant. Of course, this equation suggests a stress modification of the swelling rate, not the incubation period.

An empirical constitutive equation for the stress effect on swelling incubation dose is given as the larger of [48]:

$$\tau_e = \tau - q(T) \, \sigma_h \tag{5}$$

$$\tau_e = 0.5 \tag{6}$$

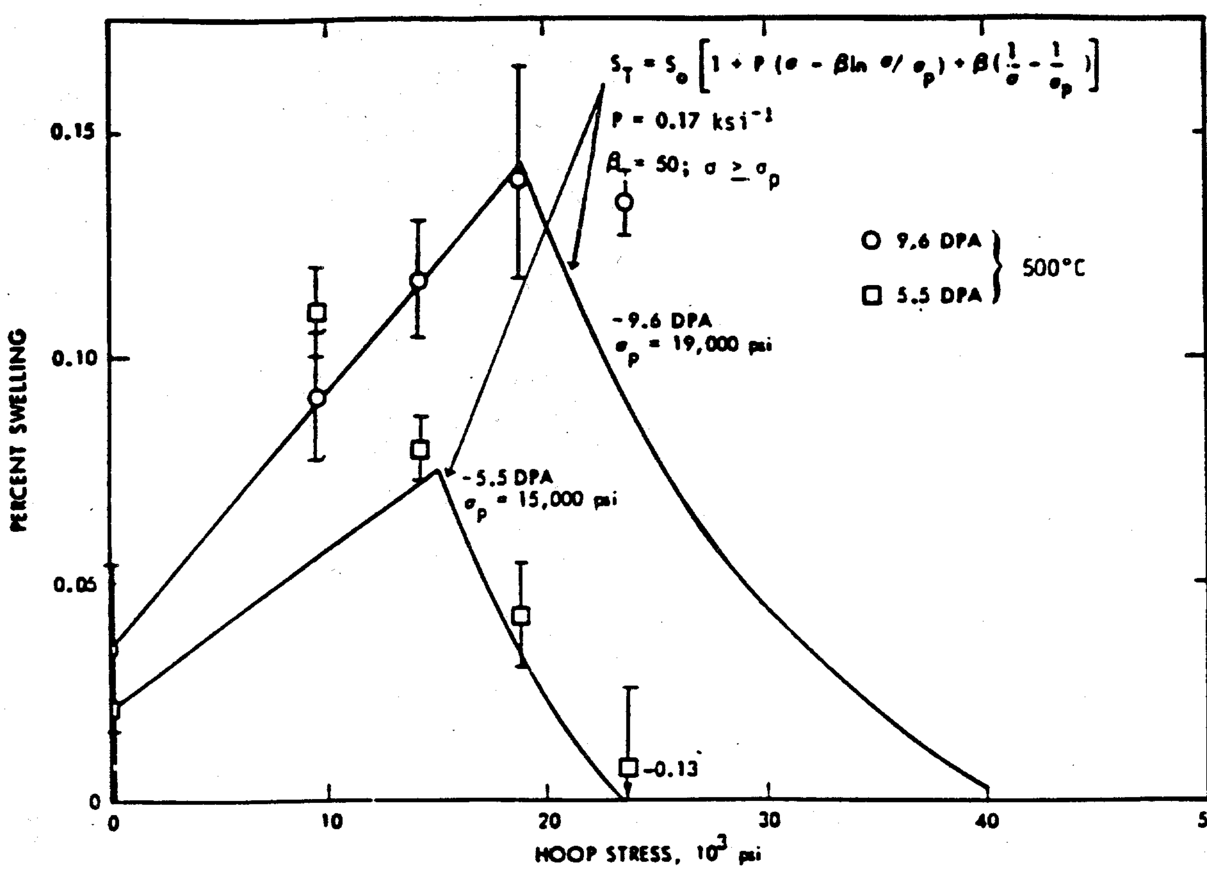

Fig. 7. Effects of stress on swelling in annealed 316 SS pressurized tubes at 5.5 and 9.6 dpa (500°C) [17].

where T is the temperature in units of °C

σ_h is the hydrostatic stress in units of MPa, $\sigma_h = \frac{1}{3} (|\sigma_x| + |\sigma_y| + |\sigma_z|)$,

τ_e is the incubation parameter in units of 10^{22} n·cm^{-2} (E > 0.1 MeV),

q(T) expressed in the units of 10^{22} n·cm^{-2}· MPa^{-1} is calculated [59] from

$$q(T) = q_0 + \exp\left[a - Q' / (T + 273) \right] \qquad (7)$$

where q_0 = 0.013, a = 51.4, Q' = 50,000 in units of °C^{-1}.

Straightforward use of the stress effect on incubation dose in fusion designs is complicated by the presence of time-varying stress histories. A formalism, called the Incubation Averaged Fluence (IAF) technique [19,24], has been developed so that this behavior can be included in calculations of the stress effect on incubation dose. The IAF, f(t), is defined as [19,24]

$$f(t) = \int_0^t \frac{\phi(t')}{\tau_e(t')} dt' \ . \qquad (8)$$

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 in calculating τ_e from the above equation describing the dependence of incubation dose on stress. 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. The IAF method was used recently in a stress analysis of a duplex structure for a DEMO reactor [63]. Results clearly indicated that stress-enhanced swelling may enhance swelling to values that reached two folds of the stress free case.

3. Irradiation creep and its dependence on swelling

Irradiation creep is caused when external non-hydrostatic stresses are applied during irradiation. In a temperature regime where thermal creep and irradiation creep compete, the picture is that at high stress levels, thermal creep dominates. At low stress levels (<150 MPa) the deformation shows a linear stress dependence [64]. In a temperature/stress region (300-550°C), where thermal creep can be neglected, irradiation creep is weakly temperature dependent. As for dose rate, a linear correlation of creep with the damage rate is observed. This may not be true for very low irradiation temperatures [64].

3.1 Climb-controlled glide creep

There are a number of theoretical approaches proposed in the literature to explain the phenomenon of irradiation creep [see for example 64-66]. Of the different mechanisms, the mechanisms of stress-induced loop nucleation or alignment (SIPN) and stress-induced preferential absorption (SIPA) have a common feature that the formation or growth of interstitial loops or the absorption of defects at existing dislocations depends upon their orientation with respect to the external stress and therefore cause a macroscopic creep strain. The application of the SIPN model is restricted to materials with low dislocation densities, e.g, solution-annealed materials at low neutron fluences [64]. On the other hand, SIPA creep dominates at high dislocation densities and low stresses [64].

In the previous models, glide processes are neglected. Models which include dislocation glide (Climb-Controlled Glide, CCG) as a further strain contribution are of special interest in cases where the linear stress-dependence of creep deformation is no longer valid or where the creep rate increases at the onset of swelling [64]. The contribution of strain due to dislocation glide is difficult to analyze. During the random climbing of the network certain segments find themselves able to glide. This glide occurs and thereby gives an increment to the irradiation creep strain. The segment is then left in a low stress locality and further glide of that and other potentially glissile segments have to wait until further climb creates the appropriate conditions. The major creep strain comes from the glide and not from the the intermediate climb [67]. In conclusion, the climb-controlled glide of dislocations past obstacles is indeed an important mechanism for irradiation creep for low fluences at all temperatures or for all fluences at high temperatures [68]. Early theoretical models proposed were heuristic in nature and, depending on the assumptions, yield a variety of stress-dependencies [65].

3.2 Modelling of stress-enhanced radiation creep

In a number of recent reports, the creep-swelling relationship has been investigated for annealed AISI 304L [65,69-71] and various thermomechanical treatments of AISI 316 stainless steel [72-79]. 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 (precipitation-related dimensional changes and transient relaxation of cold-worked-induced dislocations) and two major contributions [80]. 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 [81] and for the ferritic/martensitic alloys HT9 and 9Cr1Mo [82] which showed the same trend. It has been proposed [64,80-83] that the creep rate $\dot{\varepsilon}$ at any relevant temperature is linearly dependent on stress and related to the swelling rate $\dot{S}$ by the following relation:

$$\frac{\dot{\varepsilon}}{\sigma} = B_0 + D_0\,\dot{S}\,. \tag{9}$$

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 [83]. 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 9 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 dominating the irradiation creep behavior [83]. 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 [64].

It has been commonly accepted that the irradiation-induced creep rate accelerates with the onset of swelling and that it will continue at a rate proportional to that of the swelling. However, some research indicated that the creep rate in AISI 316 stainless steel subsequently declines as swelling approaches levels in excess of 5% (For dpa <50, and at 550°C) [72,84]. 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 [84]. 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.

4. Conclusions

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 dpa levels as well as high coolant temperatures (i.e., high primary stress levels). Swelling-enhanced creep is a complementary process that should be taken into consideration, otherwise, overprediction of swelling levels may result. The impact of the two effects on the lifetime calculations should be analyzed in the relevant fusion reactor stresses. The two phenomena are especially important for the prediction of the irradiation behavior of bonded structures.

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 understood so that the influence of the different variables relevant to fusion applications can be included in an expansion of the incubation parameter τ such that

$$\tau = \tau_0(T) + q_1\ f(\text{stress}) + q_2\ f(\text{dpa rate}) + q_3\ f(\text{He/dpa}) + \ldots$$

where q's are constants possibly dependent on temperatures.

There is a complete lack of data on the effect of stress on the swelling as well as the relationship between swelling and creep for materials other than stainless steel. Even for steel, more data is still needed. The determination of stress effects on microstructural evolution requires that experimental observations be limited to a single, well-defined heat with consistent thermal-mechanical treatments and that microstructural data be extracted from stressed and unstressed specimens irradiated together as well as irradiating bonded structures.

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