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Parametric study of irradiation effects on the ductile damage and flow stress behavior in ferritic-martensitic steels

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A B S T R A C T

Ferritic-martensitic steels are currently being considered as structural materials in fusion and Gen-IV nuclear reactors. These materials are expected to experience high dose radiation, which can increase their ductile to brittle transition temperature and susceptibility to failure during operation. Hence, to estimate the safe operational life of the reactors, precise evaluation of the ductile to brittle transition temperatures of ferritic-martensitic steels is necessary. Owing to the scarcity of irradiated samples, particularly at high dose levels, micro-mechanistic models are being employed to predict the shifts in the ductile to brittle transition temperatures. These models consider the ductile damage evolution, in the form of nucleation, growth and coalescence of voids; and the brittle fracture, in the form of probabilistic cleavage initiation, to estimate the influence of irradiation on the ductile to brittle transition temperature. However, the assessment of irradiation dependent material parameters is challenging and influences the accuracy of these models. In the present study, the effects of irradiation on the overall flow stress and ductile damage behavior of two ferritic-martensitic steels is parametrically investigated. The results indicate that the ductile damage model parameters are mostly insensitive to irradiation levels at higher dose levels though the resulting flow stress behavior varies significantly.

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1. Introduction

The fracture properties of ferritic-martensitic (F/M) steels show large variation with temperature. Cleavage mode of fracture with limited crack tip plasticity is typically observed at lower temperatures, and is associated with low fracture toughness values (lower shelf). At higher temperatures, ductile mode of fracture with the nucleation of voids, their growth and coalescence is the dominant failure mechanism, which increases the fracture toughness values substantially (upper shelf). In the transition regime, between the lower and upper shelves, unstable cleavage fracture is preceded by ductile damage. Also, a large scatter in the fracture toughness values can be observed owing to the inherent statistical nature of cleavage fracture. Irradiation induces additional lattice defects, which reduces the ductility of the material and hence increases the ductile to brittle transition temperature (DBTT). Such irradiation-induced embrittlement of the steels increases their failure probability and can limit the operational life of the reactors. Hence, the development of models considering the influence of irradiation on the fracture behavior of steels is necessary to accurately determine the maximum operational life of the reactors.

The master-curve approach is typically used to obtain the DBTT in steels [1–5]. It is based on fitting the experimentally obtained fracture toughness data with the modified Weibull distribution function. In this approach, the temperature that provides a median fracture toughness of $100\text{Mpa}\sqrt{\text{m}}$ for a 25 mm thick compact tension fracture toughness testing specimen is considered as the DBTT. However, the master-curve equation is based on the assumption of small-scale yielding, which occurs near the lower-shelf and lower failure probabilities near the upper shelf. Large-scale ductile damage and plasticity occurring at higher failure probabilities near the upper shelf is not considered in the master-curve equation. In addition, owing to the limited availability of the irradiated specimens, the determination of the DBTT using the master-curve approach may not be always feasible. Hence in recent years, micromechanistic computational approach has been pursued [6,7] to overcome these shortcomings. Ductile damage models [8,9] in conjunction with weakest link theory based criterion [10–14], to predict onset of cleavage fracture, are used in this approach. The parameters of the ductile damage and the weakest link theory

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based models are calibrated from fracture tests at a temperature on the upper and lower shelf, respectively and are assumed to remain constant. The temperature dependent flow stress behavior is then used to predict the probabilistic fracture toughness/energy release values in the transition regime. This approach has been used to predict the DBTT of unirradiated steels and satisfactory agreement with experiments could be obtained [6,7]. A unified cohesive zone model requiring minimum calibration effort has also been developed in Ref. [15] to predict the DBT of fracture toughness for unirradiated low alloy pressure vessel steel.

Irradiation can cause the formation of vacancy and self-interstitial atom, SIA, type defect loops and precipitates [16]. Initially these loops and the precipitates hinder the motion of gliding dislocations that increases the yield stress of the irradiated material. However, the gliding dislocations subsequently absorb the loops to create defect-free bands or clear-channels [17]. The formation of these clear-channels is able to explain the reduction in subsequent strain hardening capacity and immediate softening after initial yielding, in highly irradiated ferritic and F/M steels [18]. Irradiation may also affect the ductile damage and cleavage fracture modes in addition to modifying the flow stress behavior. To accommodate these variations, irradiation dependent ductile damage and cleavage initiation model parameters has been used in Ref. [19] to accurately predict the transition of Charpy energy in A508 pressure vessel steel. A decreasing Weibull stress with irradiation dose has been used in the cleavage initiation model [19], which signifies that irradiation decreases the resistance to microcrack propagation in the matrix prior to unstable failure. However, such irradiation dependency of cleavage fracture stress has not been seen in Refs. [20,21]. For the ductile damage model parameters, an increase in the void volume fraction and nucleation rate with irradiation has been assumed to explain the corresponding decrease in the upper shelf energy [19]. This assumption has been rationalized based on weakening of inclusion interfaces due to phosphorous segregation [22] since irradiation induced defect sizes are too small to influence the void nucleation mechanism [23,24]. Though the DBTT shift has been satisfactorily predicted in Refs. [19], further investigations are necessary to confirm the assumptions and reduce the recalibration effort for the irradiated F/M steels.

In the present work, the tensile data of T91 and EUROFER97, irradiated at 300 °C to different dose levels and tested at the same temperature [25], is considered for the numerical investigation. Ductile fracture of irradiated T91 and EUROFER97 has been observed to be strongly strain-rate sensitive [26,27]. However, in the present work the quasi-static ductile fracture occurring at very low strain-rates (10^{-4}/s) is investigated by utilizing the corresponding experimental data [25]. Also, the parametric study is performed to numerically quantify the extent of influence of the flow stress and void nucleation/growth/coalescence parameters on the ductility of the two types of F/M steels.

Although, both these alloys have the same Cr content (~9 wt%), however, the differences in the concentrations of P, Mo and Ni give a significant dissimilarity in their overall stress-strain behavior. A comparison of the chemical compositions of these two alloys is shown in Table 1 [25]. Both alloys have similar martensitic lath structure as observed from TEM images of the unirradiated specimens [25]. Carbides of type $M_{23}C_6$ are found on grain/sub-grain boundaries in both these alloys with the same size distribution. However, the differences in prior austenitic grain size, carbide distribution and dislocation sub-structure between the unirradiated alloys is hypothesized to cause the variations in stress-strain evolution and ductility. After irradiation, T91 is observed to have smaller and more homogeneously distributed defect loop structure than EUROFER97 and hence shows higher ductility for the same dose level [25].

In this work, a parametric study is performed by utilizing the tensile stress-strain data to relate the influence of irradiation on the ductile damage and flow stress model parameters in these two steels. The organization of the paper is as follows. In Section 2, a detailed description of the ductile damage, flow stress models and the finite element method (FEM) is provided. The comparisons between the simulated and experimental stress-strain evolution are described in Section 3 followed by a discussion on the sensitivity of the model parameters to irradiation. The paper is concluded in Section 4.

2. FEM model

The tensile experiments of T91 and EUROFER97 have been performed on round specimens with a diameter of 2.4 mm and gauge length of 12 mm as provided in ref. [25]. The experimental data of specimens that have been irradiated at 300 °C to dose levels of 0.06, 0.6, 1.5 dpa and tested at the same temperature, is considered. An axisymmetric FEM model with the same dimensions is used to perform the analyses and is shown in Fig. 1. To ensure that necking takes place at the center of the sample, a small radial offset is introduced, following [28], and is shown in Fig. 1. The radial offset incorporates the effect of geometrical and material imperfections that can cause bifurcation and onset of axisymmetric necking in round tensile testing specimens. Bifurcation occurs when the stress required to sustain an increased load following a reduction of area exceeds the material-hardening rate. A numerical study in Ref. [29] using elasto-plastic constitutive laws shows that the imperfect geometry with an appropriate radial offset can estimate the bifurcation point obtained from the simulations of the full perfect geometry. An optimal offset value, $\Delta R/R = 0.4\%$ similar to [28], is chosen in the present work. The 8-noded isoparametric element with reduced integration is used for discretizing the specimen geometry. A mesh sensitivity study by doubling and halving the mesh size is performed, and no significant difference in the stress-strain behavior is observed till near the final failure.

The constitutive behavior for deformation and failure is based on the rate independent ductile damage model developed by Gurson [9] and later modified by Tvergaard and Needleman [28,30]. In this model, following the large deformation theory, the plastic component of rate of deformation tensor, $\underline{D}^p$, is represented by:

Table 1
Chemical composition of T91 and EUROFER97 (wt%) [25].

Steel	Cr	C	Mo	W	Ta	V	Mn	Ni	Si	Nb	P
T91	8.32	0.1	0.96	<0.01	~	0.24	0.43	0.24	0.32	0.06	0.02
E97	8.96	0.12	<0.001	1.1	0.13	0.19	0.43	0.007	0.07	<0.001	<0.005

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