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Specification of stress limits for irradiated 316L(N)-IG steel in ITER structural design criteria

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Abstract

Austenitic steel 316L(N)-IG is one of the structural materials used in the ITER in-vessel components. For the design analysis properties of irradiated material are required. These are both stress and strain limits listed in ITER Structural Design Criteria (SDC-IC). Experimental data base on tensile properties includes irradiation up to dose of about 15 dpa in temperature range 70–500 °C. The analysis shows three temperature intervals to be treated in analysis: 20–230, 230–300 and >300 °C. For these three temperature intervals, best fit equations have been proposed. The analysis also included calculation of −95% confidence level of strength and ductility, as it is required in SDC-IC. S_e and S_d stress limits have been also calculated for irradiated 316L(N)-IG steel. Those stress limits should be used in the temperature range 230–300 °C due to exhaustion of strain hardening capability of the material and decreases of uniform elongation below 2%.

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1. Introduction

It is known that properties of materials are substantially changed due to reactor irradiation. The hardening and loss of capability for deformation hardening are usually observed for low temperature irradiation (∼<0.3 T_{melt}). There are no known national standards or codes adequately accounting for the irradiation effects on mechanical properties and design allowable for structural materials. The interim structural design criteria (SDC-IC) developed for ITER include some rules for prevention of fracture due to irradiation embrittlement and loss of work hardening capability. In addition to commonly used stress limits (like S_m) the new stress limits have been introduced. These are temperature and neutron fluence dependent values S_e and S_d for the limitation of primary plus secondary membrane stresses and total stresses, respectively [1]. Average and minimum (for −95% confidence) tensile strength and ductility are necessary as function of temperature and damage dose for the calculation of $S_e(T, \phi t)$ and $S_d(T, \phi t)$.

2. Tensile strength and ductility of irradiated 316L(N)-IG steel

The tensile strength and ductility can be estimated on the bases of results of ITER R&D performed during the engineering design activity and accumulated in the materials data base (MDB). Preliminary selection of data has been performed to provide appropriate data for the base metal of 316L(N)-IG steel satisfying the ITER specification. About 200 experimental tensile data points have been used for analyses that covered dose–temperature intervals up to 15 dpa in the temperature range 80–400 °C. Surfaces of $S_u(T, \text{dpa})$, $S_y(T, \text{dpa})$ and $\varepsilon_{un}(T, \text{dpa})$ have been estimated in the 3D best fit of tensile strength, yield strength and uniform elongation, respectively. Only data with the test temperature equal to the irradiation temperature were used for analysis. The surfaces have been estimated by the minimisation of the sum of the square deviations of experimental values from the estimated ones for each property. Result of

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statistical evaluation of yield strength is presented in Fig. 1.

The temperature–dose dependence of yield strength presented in Fig. 1 reflects the typical behaviour of austenitic steel under irradiation. Fast hardening during low irradiation doses (~0.5–1 dpa) with the tendency to saturation with increasing irradiation dose is observed for the low temperature region ($\sim\leqslant 150$ °C). Increasing irradiation temperature to ~200–300 °C results in increased irradiation hardening. The strength approaches to the saturation level at higher irradiation doses. Subsequent increase the irradiation temperature resulted in decrease of the hardening value.

Analysis of ductility shows that the uniform elongation of steel falls below 2% in the temperature range ~200–350 °C at irradiation doses above 4 dpa (see Fig. 2). This temperature region is the most critical for the fracture of steel due to exhaustion of ductility due to irradiation. Stress limits S_e and S_d become critical for the assessment of structural integrity of components.

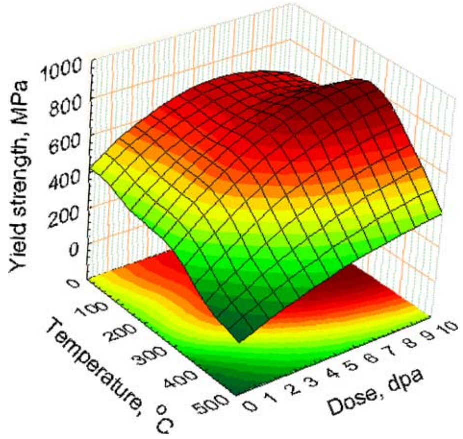


Fig. 1. Interpolated dose–temperature dependence of yield strength for 316L(N)-IG steel.

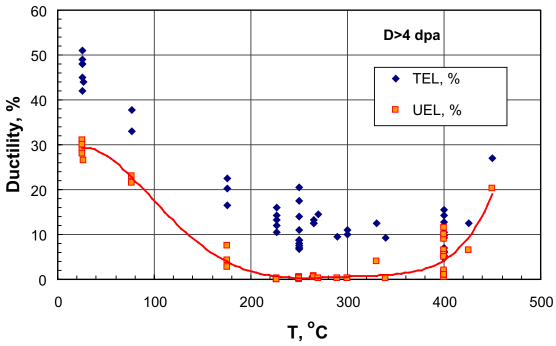


Fig. 2. Ductility of irradiated 316L(N)-IG steel for irradiation doses exceeding 4 dpa. (UEL and TEL – uniform and total elongations, respectively.)

Therefore, analysis of data shows that three irradiation temperature ranges can be conventionally defined: ~20–200, ~200–330, ~330–400 °C. We do not consider here the temperatures above 400 °C because this is out of ITER working temperatures and the available data base includes only data for temperatures up to 400 °C.

It seems reasonable to find the best fit equations for the dose dependences of properties for the three defined temperature intervals, and it is clear that the most appropriate equations should follow from the theoretical models describing the steel behaviour under irradiation.

3. Models of strengthening

The observed changes of tensile properties depend on the evolution of microstructure under irradiation. As shown in [2–4] the stacking fault tetrahedra (SFT) and Frank loops are responsible for the irradiation hardening of steel at low temperatures ~<200 °C. The fraction of SFT can reach 80–90% with sizes of about 1–2 nm. The concentration of such defects increases with increasing irradiation dose, but the sizes remain approximately the same. It means that these defects are formed directly in the cascades (subcascades). These defects are revealed as 'black dots' by electron microscopy observation.

The density of 'black dots' decreases with increasing of irradiation temperature, but the density of Frank loops is increased. Some voids appear in the structure and their density is also increased with increasing of irradiation temperature (in particular for the high He/dpa ratio) [4,5]. It can be thus concluded that Frank loops are responsible for the strengthening of steel in the temperature range ~200–330 °C [4–6].

For higher temperatures several defects, including Frank loops, bubbles, voids and precipitates, define the strengthening of material.

The value of increasing strength can be expressed by the following equation (see for example [7]):

$$\Delta\sigma = \alpha MGb\sqrt{(Nd)}, \tag{1}$$

where G is the shear modulus, b – Burgers vector, M – Taylor factor, α – hardening coefficient depending on the type of defects, N and d – density and size of defects, respectively.

For a description of SFT accumulation rate at low temperatures we will use a model similar to one developed by Kiritani [3]. If it is assumed that SFT are formed in cascades (subcascades) with the rate n_1, but they can be destroyed by mobile interstitials and by small clusters from more energetic cascades created with rate n_2 in the volume V_2 around the SFT, the following equation describes for the SFT accumulation rate:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = (1 - NV_1) \cdot n_1 - NV_2 \cdot \frac{aN}{aN + b\rho} \cdot n_2 - cN, \qquad (2)$$

where N is the SFT concentration, ρ – density of sinks in the matrix (dislocations) except the cascade regions, a and b – sink constants, $c(T)$ – thermal annealing rate of SFT. Assuming that $aN \ll b\rho$ for the high dose of irradiation, the solution of Eq. (2) resulted in the following dependence of defects density:

$$N = N_s \cdot (1 - \exp(-t/t_0)), \qquad (3)$$

where $N_s = 1/(V_1 + V_2 n_2/n_1 + c/n_1)$ and $t_0 = N_s/n_1$. Substituting (3) into (1) will give the following dependence for strengthening:

$$\Delta\sigma \propto (1 - \exp(-D/D_0))^{0.5}. \qquad (4)$$

Here D_0 is constant, D – dose of irradiation.

Similar dependence can be derived for the intermediate temperature range ~200–330 °C, where hardening is defined mainly by the Frank loops. In this case only the first term in Eq. (2) for Frank loops should be used.

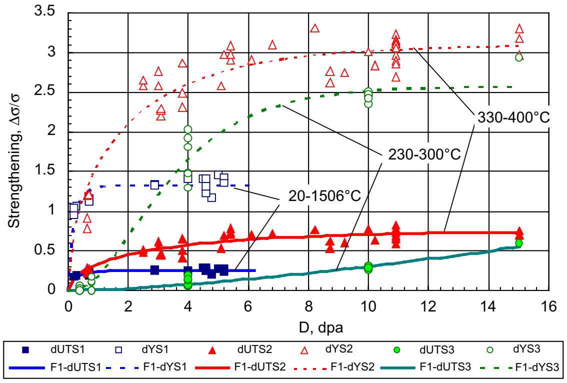
For the high temperature range, >330 °C, the changes in strength depend in addition on the bubbles, cavities and precipitates formed and grown under irradiation. There might be two options: either use Eq. (4) or use a power function. If in the initial stage the hardening is due to formation of cascades, then the first can be used up to some dose D_0. The power function may apply after D_0 instead of saturation, if it is assumed that strengthening is defined mainly by the loops and voids. The utilisation of rate theory for their growth, it is possible to get a power function for the strengthening with dose of irradiation after D_0, i.e.

$$\Delta\sigma \propto t^n \quad \text{or} \quad \Delta\sigma \propto D^n, \qquad (5)$$

where n varies from 1/6 to 3/14 depending on the simplifications used for the solution of the reaction equations.

4. Best fit equations for strengthening

Eqs. (4) and (5) have been used for the best interpolation of available experimental data. All data have been divided into a three temperature ranges: 20–200, 200–330, 330–400 °C. However, some data are missing in the temperature ranges 150–230 and 300–330 °C. So, the actual temperature ranges are indicated where results of analyses are described, i.e. the analysis is related to the following intervals: 20–150, 230–300 and 330–400 °C. Results of statistical analysis are presented in Fig. 3. Correlation coefficients and differences have been analysed. The best fit equations and correlation coefficients are also presented in the figure. This shows that relatively good interpolation of experimental data for the temperature ranges 20–150 and 230–300 °C can be provided with Eq. (4). However for the higher temperature range (330–400 °C) Eq. (4) with the power number 0.5 did not provided an adequate description of data on the yield strength and ultimate strength. The more reasonable approximation has been found for an equation similar to (4) with the powers equal to ~1.46 and 2.69 for the ultimate strength and yield strength, respectively. Saturation is observed only for changes in yield strength. As for the ultimate strength, there is no saturation up to a dose of about 15 dpa. The power function (5) can also be successfully used for the changes of ultimate strength due to irradiation.



Temperature range	Fitted equations	Correlation coefficient
20-150°C	dUTS1=(0.254427)*(1-EXP(-D/(0.452632)))^0.5	0.815
	dYS1=(1.32207)*(1-EXP(-D/(0.300311)))^0.5	0.829
230-300°C	dUTS2=(0.745304)*(1-EXP(-D/(4.35091)))^0.5	0.890
	dYS2=(3.09024)*(1-EXP(-D/(3.24223)))^0.5	0.935
330-400°C	dUTS3=(1730.32)*(1-EXP(-D/(3749.67)))^(1.457714)	0.977
	dYS3=(2.573065)*(1-EXP(-D/(2.125053)))^(2.685745)	0.988

Fig. 3. Strengthening of steel under irradiation for different temperature ranges. (Designations: dUTS. dYS – difference of unirradiated and irradiated ultimate and yield strength relative to unirradiated values. Coefficients 1, 2 and 3 correspond to temperature ranges 20–150, 230–300 and 330–400 °C, respectively. F1 – curves received by the best fit equation.)

Therefore, the best fit equations given in Fig. 3 can be used for the specification of average values of ultimate and yield strength of steel 316L(N)-IG. Minimum values can be developed by reducing the average strength data to the statistically defined confidence value for the doses range to be analysed. Deviation points of average data (calculated from the best fit equations) from the experimental ones are calculated for the analysed doses range. Standard deviation is calculated for this population of deviation data. Then, the confidence value is calculated by multiplying standard deviation by 1.96 that corresponds to 95% confidence, i.e. $\Delta = \mathrm{SD} * 1.96$. The Δ value shall be subtracted from the average data points received, using the appropriate fitted equation. Thus,

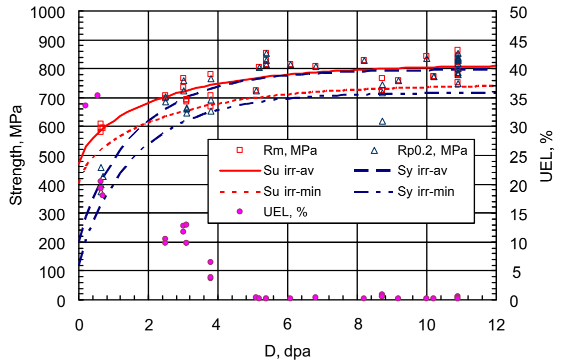


Fig. 4. Experimental and statistically calculated average and minimum tensile properties for the temperature range 230–300 °C.

minimum data are less for *Δ* compared with average data. Example of calculations for average and minimum ultimate and yield strength ($S_{u,av}$; $S_{u,min}$; $S_{y,av}$; $S_{y,min}$) for the temperature range 200–230 °C are presented in Fig. 4. The uniform elongation corresponding to that temperature range is also presented in Fig. 4. Similar calculations can be easily provided for other temperature ranges.

The most critical doses and temperatures are those where uniform elongation falls below 2% (in accordance with ITER Structural Design Criteria [1]). The work hardening capability of steel is limited for those doses and temperatures where uniform elongation is minimum. The uniform elongation remains above 2% in the temperature ranges 20–150 and 330–400 °C up to doses of 10 dpa. To prevent brittle fracture of steel components due to exhausting of ductility, as soon as uniform elongation decreases below 2%, the S_e and S_d stress limits must be used in accordance with ISDC. S_e and S_d can be calculated using data presented in Fig. 4. Substituting $S_{u,min}$ and minimum uniform elongation $\varepsilon_{u,min}$ in the equation given in ITER Interim Structural Design Criteria [1], the dose dependent S_e and S_d can be calculated. Results of calculation are presented in Fig. 5. The results of calculation confirm the previous statement that stress limits for prevention of brittle fracture are critical for doses exceeding ∼4–5 dpa at the temperatures of most significant hardening (200–300 °C). These stress limits are not critical and should not be used in other dose–temperature ranges.

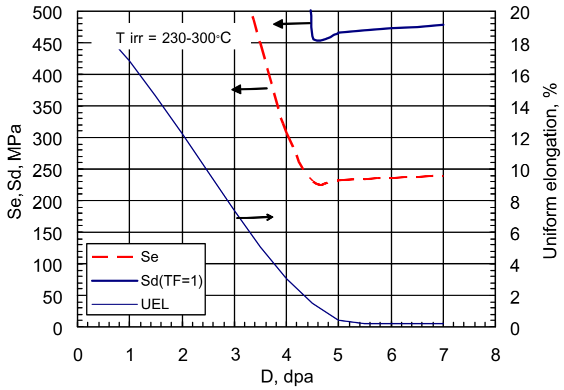


Fig. 5. Estimated stress limits S_e, S_d and minimum of uniform elongation of 316L(N)-IG steel at the temperatures 230–300 °C.

5. Conclusion

A procedure for the calculation of temperature–dose dependence of tensile strength, yield strength and elongation has been developed. Calculation of average and minimum tensile strength and yield strength for the steel 316L(N)-IG has been provided using the ITER materials data base. These values defined stress limits to prevent brittle fracture of steel components due to exhaustion of ductility (and work hardening capability) under irradiation. These stress limits are most critical for doses above 4–5 dpa in the temperature range 200–300 °C.

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