ELSEVIER

Journal of Nuclear Materials 307–311 (2002) 1011–1015

journal of nuclear materials

www.elsevier.com/locate/jnucmat

On the transition toughness of two RA martensitic steels in the irradiation hardening regime: a mechanism-based evaluation

G.R. Odette [a,*], H.J. Rathbun [a], J.W. Rensman [b], F.P. van den Broek [b]

[a] Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, CA 93106-5070, USA
[b] NRG Petten, The Netherlands

Abstract

An analysis of the transition fracture toughness and constitutive behavior of F82H and Eurofer97 reduced activation martensitic steels are presented in both unirradiated and irradiated conditions. The unirradiated toughness data for F82H show very steep temperature dependence and the Eurofer97 toughness data measured with 5 mm versus 10 mm thick specimens are systematically higher. Both of these observations indicate a loss of constraint. Constraint loss adjustments are applied using a three-dimensional finite element analysis based toughness scaling model. The adjusted F82H results can be represented by a master curve (MC) and the corresponding 5 and 10 mm adjusted data fall in the same scatter band. The 10 mm irradiated specimens, with generally lower toughness levels, suffer minimal constraint loss. The irradiation induced MC T_0 shifts (ΔT_0) are analyzed in terms of changes in constitutive properties. The ΔT_0 are generally consistent with the observed irradiation hardening. However, the effects of irradiation on post-yield strain hardening behavior must be considered to obtain self-consistent hardening-shift relations.

1. Introduction

The toughness-temperature curves, $K_{Jc}(T)$, of BCC alloys in the cleavage transition depend on numerous factors, including specimen size as a consequence of both constraint and statistical effects [1]. Size effects must be considered in evaluating irradiation induced toughness transition temperature shifts. Direct multiple temperature measurements of valid $K_{Jc}(T)$ for factorial combinations of these and a host of material and environmental variables is prohibitive. As a consequence, we have proposed a master curves (MC)-temperature shifts (ΔT) method based on the use of relatively small numbers of small to ultra-small fracture specimens [1–4]. The MC-ΔT approach is an elaboration and extension of the ASTM E1921-97 method for evaluating the transition toughness of ferritic steels [5], specifically tailored to fusion, rather than heavy section, applications. The MC-ΔT method uses a small family of generic constant-shape $K_{mc}(T - T_0)$ curves that are indexed on an absolute scale (T) relative to a reference temperature (T_0) with a relatively small number of tests, again primarily using small to very small specimens. The available $K_{Jc}(T)$ data for steels and vanadium alloys generally support the MC-ΔT concept [1,4,6].

In this paper, three dimensional finite element (FE) simulations of crack tip fields are combined with a micromechanical model to evaluate deviations from small scale yielding (SSY) and the $J_q/J_c > 1$ due to the corresponding constraint loss effects. Here J_q is the measured toughness and J_c the corresponding toughness for SSY conditions. The toughness can be represented in terms of the equivalent $K_{q/Jc} = \sqrt{J_{q/c}E'}$, where E' is the

* Corresponding author. Tel.: +1-805 893 3525; fax: +1-805 893 8651.
E-mail address: odette@engineering.ucsb.edu (G.R. Odette).

0022-3115/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01166-2

plane strain elastic modulus. For deep cracks in bending with $a/W \approx 0.5$ (where a is the crack length and W the specimen width), constraint loss arises from large-scale deformation. Deformation at cleavage fracture is typically characterized by a non-dimensional parameter $M = b\sigma_y/J_q$, where b is the uncracked ligament length and σ_y is the yield stress. Increasing deviations from SSY and constraint loss occur with decreasing M below $\approx$ 100 [1]. Thus, at a specified J_q, the degree of constraint loss depends on σ_y and b, giving rise to a size (b) dependence of measured toughness. The dominance of plane strain SSY also requires a sufficient specimen thickness (B), typically $B \geqslant b$. Constraint loss effects vanish in the SSY limit, but statistical size effects may persist reflecting the fact that the volume of material under high stress scales as $\approx B^{-1/4}$ [1,5]. Both the SSY $K_{Jc}(T)$ curve reference temperature T_0 and the amount of constraint loss at a specified M depend on the local fracture and post-yield strain hardening properties of the steel.

2. Experiment

The experimental K_{Jq}/K_{Jc} and tensile data analyzed in this paper are reported by Rensman and co-workers [7,8]. The two quenched and tempered martensitic stainless steels are F82H and Eurofer97, with base compositions of 8Cr–2W–0.2V–0.1C and 9Cr–1W–0.2V–0.15Ta, respectively. The F82H and Eurofer97 have similar unirradiated room temperature σ_y of $\approx$550 MPa. Two heats of the Eurofer97, which may have slightly different properties, were studied. However, these small differences are neglected in the subsequent analysis. Fracture toughness experiments were performed on compact tension $[C(T)]$ specimens with $W = 22.5$ mm, $B = 5$ and 10 mm and $a/W \approx 0.5$, following ASTM E1921-97 [5]. Out of plane crack propagation occurred in a number of specimens, but we believe that this did not greatly influence the initiation $K_{q/Jc}$ estimates. The fracture measurements were complemented by tensile tests over a range of temperatures. The steels were characterized in both the unirradiated, baseline condition and following irradiation in the HFR reactor at Petten. The F82H was irradiated to $\approx$5 dpa at $\approx$300 °C (designated as the SI-NEXT experiment) and the Eurofer97 was irradiated to $\approx$2.7 dpa at $\approx$60 °C (designated as the SIWAS experiment).

Both irradiation conditions resulted in large increases in yield stress ($\Delta\sigma_y$) and upward shifts in the toughness transition temperature regime which we will characterize in terms of ΔT_0. Both the $\Delta\sigma_y$ and ΔT_0 were larger for the higher temperature-higher dose F82H-SINEXT irradiation. In both cases the uniform elongation measured in tensile tests was reduced to low values of <1%.

3. Transition toughness model and constraint loss assessment

A number of micromechanical models have been used to describe the critical local crack tip stress field conditions for cleavage, beginning with a critical stress (σ^*) critical distance criterion proposed by Ritchie et al. (RKR) [9]. An extension of the RKR model assumes cleavage occurs when a two-dimensional in-plane normal stress contour (σ_{22}) equals a critical stress (σ^*) and encompasses a critical area (A^*) in front of the crack [1,10,11]. Other extensions of the RKR model are based on weakest link statistics and critically stressed volume criteria [12,13]. Within this model framework, the σ^*–A^* are the material's basic local fracture properties that can be used along with the constitutive law to compute $K_{Jc}(T)$ for SSY conditions [11], and, more generally, K_q for conditions deviating from SSY constraint, (e.g. small specimens, thin specimens, shallow and/or surface cracks) [4,12]. The stressed area, A, can be evaluated using FE simulations and specified constitutive laws appropriate to the given material [1,10–13].

For a specified strain hardening law in SSY, Nevelainen and Dodds [14] showed that the self-similar stress fields can be analytically represented in terms of a non-dimensional stressed area (A') within a specified normalized stress contour ($R = \sigma_{22}/\sigma_y$):

$$A' = \log[A\sigma_y^2\varepsilon_y^2/J_{SSY}], \tag{1}$$

where ε_y is the yield strain $= \sigma_y/E$. By substituting appropriate values of $\sigma_{22} = \sigma^*$, $\sigma_y(T)$ and A^*, $J_c(T)$, and hence $K_{Jc}(T)$, can be directly computed [12]. This deterministic relation is strictly valid only in a temperature range where $\sigma_{22\,max} > \sigma^*$; nominally cleavage cannot occur above this temperature, giving way to ductile fracture.

The empirical observation that the $K_{Jc}(T)$ curve for ferritic materials has a constant MC shape, independent of the specific alloy and irradiation condition, forms the basis of ASTM E1921-97 [5]. This MC shape is given by:

$$K_{Jc} = 30 + 70[\exp\{0.019(T - T_0)\}] \quad (\mathrm{MPa}\sqrt{\mathrm{m}}). \tag{2}$$

FE calculations employing a power law hardening approximation to the F82H material were used to predict the SSY $K_{Jc}(T)$ using the σ^*–A^* model. It is assumed that both the σ^* and A^* are constant at low temperature. The model prediction along with the MC shape with $T_0 \approx -115$ °C is shown in Fig. 1(a) along with the unirradiated F82H data. Good agreement is achieved for $\sigma^* = 2470$ MPa and $A^* = 2 \times 10^{-8}$ m^2 in the lower knee toughness-temperature regime. The σ^*–A^* model yields a slightly steeper slope due to the very low T_0, hence, stronger temperature dependence of σ_y. However, as a result of constraint loss at higher temperature the

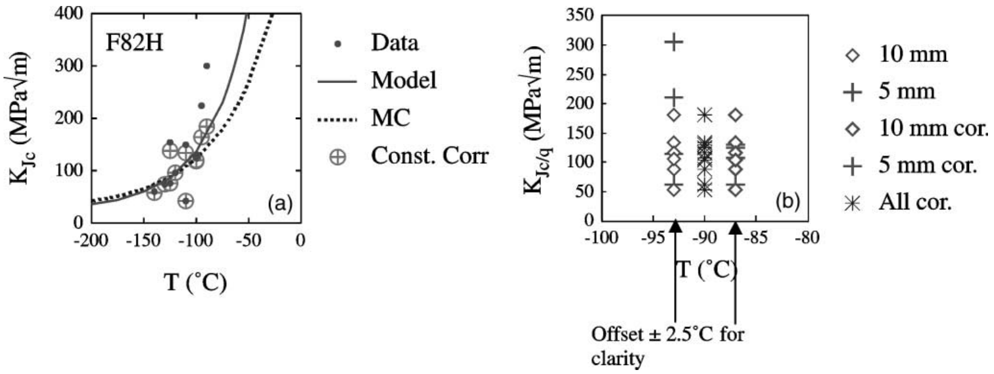

Fig. 1. Unirradiated toughness: (a) F82H compared to both the $\sigma^* - A^*$ model and MC predictions with and without constraint adjustment; and (b) Eurofer97 at −90 °C with and without constraint adjustment.

toughness data falls above both the MC and σ^*–A^* predicted curves.

An assessment of both in-plane and lateral constraint effects associated with deviations from SSY were carried out using the ABAQUS finite element code [15] to simulate the three-dimensional $C(T)$ geometry up to large scale yielding levels of specimen deformation (low values of M down to <30). Plane strain SSY reference solutions were obtained using a boundary layer model following the work of Nevelainen and Dodds [14]. Empirical $\sigma(\varepsilon)$ constitutive laws fit to experimental results were used in the FEA simulations to model both F82H and Eurofer97 steels.

The toughness scaling procedure involves calculating the J_q that provides the same stressed area A as the J_c. The J_q/J_c ($\geqslant 1$) ratio is a function of $R(= \sigma^*/\sigma_y)$, the constitutive law, the cracked body geometry and the deformation level (M). Lateral constraint effects are addressed by calculating an average area across the specimen thickness within the specified $R(\sigma_{22} = \sigma^*)$ stress contour. Hence, deviations from SSY are larger for the thinner ($B = 5$ mm) as compared to the thicker ($B = 10$ mm) specimens.

For the unirradiated F82H, $\sigma^* = 2470$ MPa, as found by fitting the σ^*–A^* $K_{Jc}(T)$ model to the measured toughness, gives a $R \approx 3.4$. The corresponding R for the unirradiated Eurofer97 and both irradiated steels were scaled to this value based on ratios of maximum σ_{22}/σ_y stress. The maximum σ_{22}/σ_y depends on the strain hardening. This gives $R \approx 3.0$ for the unirradiated Eurofer97 and $R \approx 2.7$ for both the irradiated steels assuming perfectly plastic (no strain hardening) behavior [16,17].

Fig. 1(a) and (b) show the results of applying the toughness scaling procedure for the unirradiated F82H over a range of temperature and for Eurofer97 at −90 °C. The constraint adjusted F82H toughness data is consistent with both the σ^*–A^* model prediction and reasonably consistent with the MC shape. As shown in Fig. 1(b) for Eurofer97, the magnitude of constraint adjustment is much larger for the $B = 5$ mm specimens as compared to the $B = 10$ mm specimens, indicating that the former experience substantial out-of-plane constraint loss. However, the mean adjusted toughness for $B = 5$ mm specimens is $\approx$78 MPa$\sqrt{m}$ versus 93 MPa$\sqrt{m}$ for $B = 10$ mm. This may suggest that the constraint loss adjustment is somewhat too large in this case. This difference may be due to the approximate estimate of R (higher R would result in smaller adjustments). However, both sets of adjusted data fall in the same scatter band. It should be noted that the statistical sampling volume effect of B has not been treated in this analysis. Application of a $B^{-1/4}$ scaling adjustment would decrease the toughness for the $B = 5$ mm specimens even further. The corresponding constraint loss adjustments for the irradiated specimens were found to be modest to minimal.

4. Analysis of irradiation induced shifts in T_0

The T_0 for the irradiated and unirradiated steels were found by fitting the MC shape to the adjusted data shown in Fig. 2. Since the 5 mm data from the F82H-SINEXT experiment systematically fell above the corresponding 10 mm results, partially as a consequence of constraint loss, they were not used in the T_0 fit. Note that while constraint adjustments were modest in this case, a statistical $B^{-1/4}$ adjustment would result in better agreement between 5 and 10 mm data. The resulting ΔT_0 was $\approx$235 °C for F82H-SINEXT and $\approx$128 °C for Eurofer97-SIWAS. The corresponding $\Delta\sigma_y \approx 365$ MPa for F82H-SINEXT and $\approx$290 MPa Eurofer97-SIWAS are very large in both cases. As is typical of alloys irradiated at these conditions, the uniform strain is reduced to negligible values with the immediate onset of necking. This behavior is indicative of a substantial

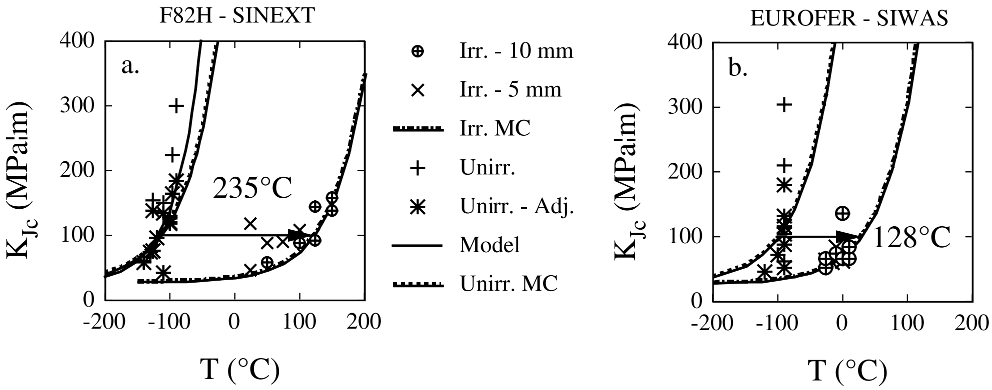

Fig. 2. Unirradiated and irradiated toughness with MC fits to estimate T_0: (a) F82H-SINEXT; and (b) Eurofer97-SIWAS.

reduction in the overall true stress-strain hardening including a small region of softening at low strains [16,17].

Thus, the ΔT_0 can be attributed to the large amount of irradiation hardening. The $\Delta T_0/\Delta\sigma_y$ for low dose fission reactor irradiations of reactor pressure vessel (RPV) is ≈0.7 and is generally expected to be similar in the martensitic F82H and Eurofer97 alloys [12]. The $\Delta T_0/\Delta\sigma_y \approx 0.64$ for the F82H-SINEXT data is in reasonable agreement with this expectation. However, $\Delta T_0/\Delta\sigma_y \approx 0.44$ for Eurofer97-SIWAS data is much lower than expected. This difference is believed to be the consequence of the strain softening or very low strain hardening in the higher dose SINEXT and SIWAS irradiations, compared to the RPV case. The peak stresses in front of a blunting crack occur at a few percent effective strain. Thus, for the present case, the appropriate relation is between ΔT_0 and the change in flow stress ($\Delta\sigma_f$) in this strain range rather than $\Delta\sigma_y$. Fig. 3 shows a blow-up of the low strain range for the F82H-SINEXT and Eurofer97-SIWAS tensile curves. The post-yield drop-off in the engineering flow stress is somewhat faster for the SIWAS 60 °C irradiation. The $\Delta\sigma_f$ at 1% engineering strain (a few percent true strain) are ≈290 and 190 MPa for F82H-SINEXT and Eurofer97-SIWAS, respectively. The corresponding $\Delta T_0/\Delta\sigma_f$ are 0.71 (F82H-SINEXT) and 0.67 °C/MPa (Eurofer97-SIWAS), in good agreement with the expected value. Thus, post yield constitutive properties, including strain softening or low strain hardening, play a key role in embrittlement. The larger differences between $\Delta\sigma_f$ and $\Delta\sigma_y$ for the Eurofer-SIWAS 60 °C irradiation case is probably associated with finer defects formed at the lower irradiation temperature that are more easily destroyed by strain, resulting in more rapid initial engineering strain softening.

5. Summary and conclusions

The transition toughness behavior of F82H is consistent with a σ^*–A^* local fracture model and MC $K_{Jc}(T)$ type curve shape. Significant constraint loss effects are evident at higher toughness in both the measured F82H and Eurofer97 data, particularly in thinner specimens. However, adjustments of the data to SSY conditions can be based on three-dimensional FE analysis using a

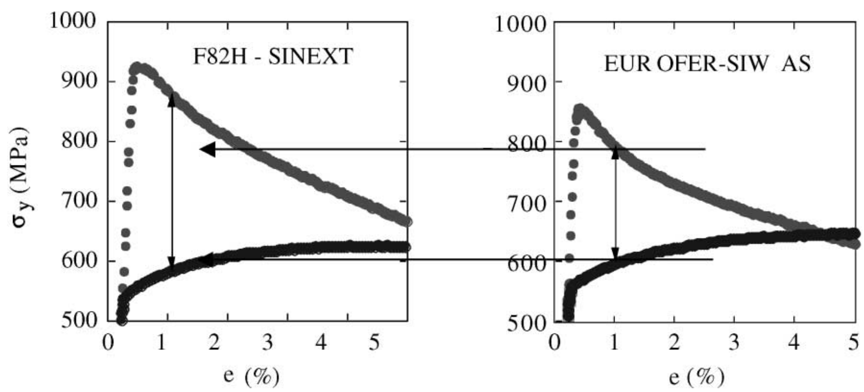

Fig. 3. Blow-up of engineering stress–strain tensile data at ≈ T_0 for F82H-SINEXT and Eurofer97-SIWAS.

stressed area scaling approach. The large shift in reference temperature T_0, is consistent with irradiation hardening if the effects of engineering strain softening are accounted for. Advanced micromechanical and statistical models are currently under development to address these and other issues.

Acknowledgements

This work was supported in part by the US Office of Fusion Energy Sciences, grant no. DE-FG03-94ER-54275, the European Fusion Technology Program and the Netherlands Ministry of Economic Affairs.

References

[1] H.J. Rathbun, G.R. Odette, M.Y. He, in: K. Ravi Chandar et al. (Eds.), Advances in Fracture Research: Proceedings of the 10th International Congress on Fracture, 2001, paper number 09120R.
[2] G.R. Odette, K. Edsinger, G.E. Lucas, E. Donahue, in: W.R. Corwin et al. (Eds.), Small Specimen Test Techniques, ASTM-STP-1328, American Society for Testing and Material, West Conshohocken, PA, 1998, p. 298.
[3] G.R. Odette, M.Y. He, Micromechanical Modeling of Master Curve Temperature Shifts Due To Constraint Loss, these Proceedings.
[4] G.R. Odette, M.Y. He, D. Gragg, D. Klingensmith, G.E. Lucas, Some Recent Innovations in Small Specimen Testing, these Proceedings.
[5] ASTM E 1921–97, Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, 2001 Annual Book of ASTM Standards V03.01, 2001.
[6] E.G. Donahue, G.R. Odette, G.E. Lucas, J. Nucl. Mater. 283–287 (2000) 518.
[7] J.W. Rensman et al., Tensile and Impact Properties of RAFM Steel Plate and Welds Irradiated up to 10 dpa at 300 °C, these Proceedings.
[8] J.W. Rensman et al., Characteristics of Unirradiated and 60 °C 2.5 dpa Irradiated Eurofer97, these Proceedings.
[9] R.O. Ritchie, J.F. Knott, J.R. Rice, J. Mech. Phys. Solids 21 (1973) 395.
[10] G.R. Odette, J. Nucl. Mater. 212–215 (1994) 45.
[11] G.R. Odette, M.Y. He, J. Nucl. Mater. 283–287 (2000) 120.
[12] K. Wallin, in: J.G. Blauel, K.-H. Schwalbe (Eds.), Defect Assessment in Components – Fundamentals and Applications, ESIS/EGF9, Mechanical Engineering Publications, London, 1991, p. 415.
[13] X. Gao, R.H. Dodds Jr., Int. J. Fract. 102 (2000) 43.
[14] M. Nevalainen, R.H. Dodds Jr., Int. J. Fract. 74 (1995) 131.
[15] ABAQUS V5.8, ABAQUS Standard Users Manual, Hibbitt, Karlsson and Sorenson Inc., Providence, Rhode Island, 1998.
[16] G.R. Odette, M.Y. He, E.G. Donahue, G.E. Lucas, in: M. Sokolov et al. (Eds.), Small Specimen Test Techniques-IV, ASTM SPT 1418, American Society for Testing and Materials, West Conshohocken, PA, 2002, p. 221.
[17] G.R. Odette, Ming Y. He, E.G. Donahue, P. Spatig, T. Yamamoto, Modeling the Multiscale Mechanics of Flow Localization-Ductility Loss in Irradiation Damaged BCC Alloys, these Proceedings.