§43. Development of Size Effects Adjustment Technique for Evaluating Fracture Toughness of Vanadium Alloy Using Small Specimens

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Vanadium alloys in the composition range around V-4Cr-4Ti have been proposed as candidate materials for fusion reactor applications and structures. One of the major concerns on the application of the alloys is irradiation embrittlement, which is measured as shifts in reference temperatures of fracture toughness transition. Assessment of the fracture toughness after irradiation requires use of small specimens primarily due to the limited space and high heating rate during irradiation. The fracture toughness measured using small specimens, however, is generally higher than those obtained from larger specimens primarily due to 1) constraint loss (CL) due to small ligament size, b, and 2) statistical stressed volume (SSV) effect that depends on the thickness, B. The CL leads to reduction of stressed area compared to small scale yielding (SSY) condition. Thus it requires higher loading in large scale yielding (LSY) in small specimens than in SSY to make the crack tip stress filed into a given size. The SSV effects are related to crack tip stressed volume that envelopes weakest link. Since stressed area scales with K_J to the power of 4 in SSY condition, it leads to the K_J scaling to $B^{-1/4}$ for a given volume, while actual data trend in RPV steels follows $K_{Jr}=[K_{Jc}(B)-K_{min}][B_r/B]^{1/4} + K_{min}$ to give reference toughness K_{Jr} for a reference B_r, where K_{min}=20MPa√m is a minimum toughness[1,2]. Odette and co-workers have shown that physically based models can be used to adjust measured toughness (K_{Jm}) to K_{Jr} for full constraint reference conditions (plane strain, SSY for B_r=25.4mm) [2-5]. For example, application of the adjustment procedure to a large unirradiated database for F82H, K_{Jm} obtained from 13 types of specimens, resulted in a self-consistent population of K_{Jr} data well described by a single MC with a $T_o \approx$-103±3°C [3]. Further the size adjustment procedures were applied to irradiated F82H toughness measurements using small specimens, leading to transition temperature evaluation consistent with larger CT specimens [4]. Corresponding physically based size adjustment procedures need to be established for vanadium alloys. Thus, the objective of this study is to examine CL and SSV size effects in facture toughness tests of vanadium alloys as well as to develop size adjustment procedures.

Three point bend (3PB) fracture toughness specimens of NIFS-II heat V-4Cr-4Ti alloy in nine different sizes with systematic variations of thickness, B, and width, W, will be tested in this study. In order to utilize the limited amount of 6.6 mm thick plate, specimens with the largest W are prepared first, while ones with smaller B are to be machined from broken halves of larger specimens. Beside the main matrix, six of the largest specimens (B=W=6.6mm) were fabricated for pilot tests, for establishing pre-cracking conditions and common test temperature for the whole test matrix being investigated. Finite element (FE) analyses of stressed area (or volume) ahead of the crack tip are carried out both in SSY and LSY conditions, that provide bases for assessing CL and SSV effects. True stress-strain constitutive relations are derived from tensile tests using iterative FE simulation of engineering stress-strain curves with model true stress-strain inputs.

After several trials we have found a good procedure to extend a fatigue pre-crack by starting with the stress intensity factor variation (ΔK) of 13 MPa√m, then decreasing it stepwise to the final value of 7.5 MPa√m as crack extends. It takes ≈ 2 to 3x10^4 fatigue cycles to extend a pre-crack to an a/W of ≈ 0.5. Pre-cracked 3PB specimens tested at -20°C, -80°C and -196°C after annealing for 2 h at 1000°C for recrystallization as well as to outgassing hydrogen resulted in only ductile crack growth in all cases reflecting very high toughness of the recrystallized V-4Cr-4Ti alloy. In contrast earlier tests of smaller specimens with no heat treatment showed a reference temperature of ≈ -5°C in the brittle to ductile transition. In the future, we will test more of pilot specimens in an outgas only anneal at 400°C for 2 h condition, that is expected to result in a transition temperature between those two extreme cases.

Figure 1 shows examples of crack tip stress fields in FE models for LSY condition as a function of load line displacement, Δ to W ratio. In SSY condition stressed area linearly grows with loading J^2, while in the LSY condition the growth clearly slows down at Δ/W ≈ 0.04. Numerical relation of the stressed area, A, versus J loading for both conditions will be extracted using a post processing program that is under development.

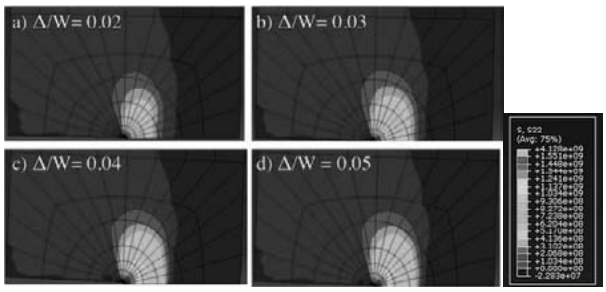

Figure 1 An example of crack tip stress field evolution in LSY condition show as a function of load line displacement Δ.

1) ASTM E 1921-09, ASTM, 2009.
2) Rathbun, H.J. et al.: *Eng. Fracture Mech*, **73** (2006) 2723.
3) Odette, G.R. et al.: *J. Nucl. Mater.* **329-333** (2004) 1243.
4) Yamamoto, T. et al.: *J. Nucl. Mater.* **367-370** (2007) 593.
5) Rathbun, H.J. et al.: *Eng. Fracture Mech*, **73** (2006) 134