§25. 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≈-103±3ºC [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 tests of previously developed specimen matrices of NIFS-II heat V-4Cr-4Ti will be carried out once a machine at NIFS or Tohoku Univ. Oarai Center becomes operational for pre-cracking. Fracture specimens of the alloys with dimensions of 3.3(W) x 1.65(B) x 18(mm) were irradiated in HFIR test reactor in Oak Ridge National Laboratory. While post-irradiation examinations are in preparation, we have tested control specimens to characterize the baseline toughness temperature transition curve over the temperature range from -196 to 20°C. Many tests resulted in a cleavage pop-in that was identified as a fracture event, while some tests showed smooth increase in load till it hits the peak. The peak was assumed to be an onset of stable crack growth. Figure 1 shows the toughness K_{JC} converted from J-integral at those characteristic points. The figure also shows a fitted toughness master curve (MC) defined in ASTM E1921. The MC provides a universal shape of median toughness temperature transition $K_{JC}(T-T_o)$ for a wide range of ferritic steels when plotted with respect to their unique reference temperature T_o. The MC shape matches the transition trend

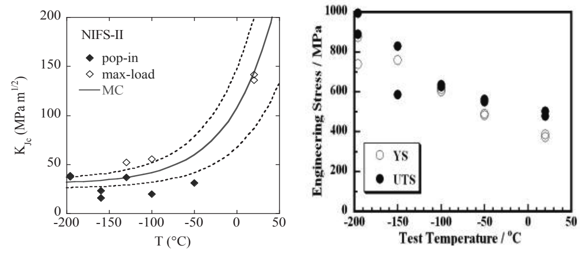

Figure 1 a. Fracture toughness, KJC, of NIFS-II heat V-4Cr-4Ti alloy as a function of temperature, with the best fit of Master curve for ferritic steels. b. Yield and ultimate tensile stress of the alloy at fracture test temperatures.

of K_{JC} of the NIFS-II alloy, while the scatter in the alloy at low temperature is larger than that for ferric steels as the 5 and 95% tolerance band only holds 40% of test results. We have also obtained tensile stress-strain curves for the toughness test temperatures required for finite element (FE) analyses of stressed area size vs. J-integral relation, that will be used to develop size scaling model. While developing a technique to derive true stress-true strain constitutive model using iterative FE simulations of engineering stress-strain curves, we have applied the technique to a cold worked alloy as a surrogate showing an immediate necking after yielding, which is often observed in irradiated BCC alloys including V alloys. Figure 2 shows that the FEM simulation with the derived true stress-true strain model reproduced the experimental curve precisely.

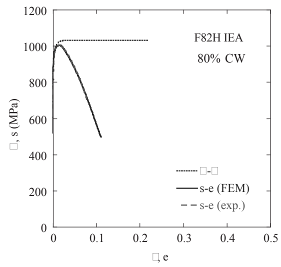

Figure 2 FEM simulated vs. experimental tensile stress strain curves with true stress – true strain model for FEM input.

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