Comparison of Irradiation-Induced Shifts of Fracture Toughness and Calculative Procedures of Regulatory Guides

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INTRODUCTION

Prevention of reactor pressure vessel (RPV) failure in light-water-cooled nuclear power reactors depends primarily on maintaining the RPV material fracture toughness at levels that will resist fracture, either brittle or ductile, during plant operation, including both normal and emergency conditions. The basic fracture toughness requirements are contained in Title 10, *Code of Federal Regulations*, Part 50 (10CFR50) with a reference to Section XI of the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code*, which contains fracture toughness (K_{Ic}) and crack-arrest toughness (K_{Ia}) curves as a function of temperature normalized to a reference nil-ductility temperature (RT_{NDT}), namely, T - RT_{NDT}. Since the RPV is exposed to neutron radiation, the materials will likely be embrittled as manifested by a shift of the toughness curves to higher temperatures. The 10CFR50 includes provisions for the adjustment of RT_{NDT} due to irradiation embrittlement, while *Regulatory Guide 1.99* (RG 1.99) [1] describes general procedures for calculating such adjustment. The "adjusted reference temperature" (ART) is defined in Appendix G of 10CFR50 as "the reference temperature as adjusted for irradiation effects by adding to RT_{NDT} the temperature shift, measured at the 30-ft-lb (41-J) level, in the average Charpy curve for the irradiated material relative to that for the unirradiated material". The data that formed the basis for the calculative procedures given in RG 1.99 were Charpy 41-J shift ( ) T_{41J}) values also.

Thus, the fracture toughness curves are shifted by virtue of the change in the T_{41J}. This paper addresses this assumption relative to the database assembled from different publications where both irradiation-induced static fracture toughness and Charpy impact shifts were reported. The fracture toughness shifts are compared to Charpy impact shifts and to shifts estimated using the calculative procedures of the US NRC Regulatory Guide 1.99, the current revision of ASTM Standard E-900, and the Eason, Wright, Odette (EWO) [2] formula.

RESULT OF ANALYSIS

Depending on the specific source, different sizes of fracture toughness specimens, procedures of the K_{Jc} determination, and fitting functions were used. It was anticipated that the scatter might be reduced by using a consistent approach to analyze the published data. The master curve concept employing Weibull statistics is applied to analyze original fracture toughness data of unirradiated and irradiated pressure vessel steels. Consequently, the radiation-induced shift of fracture toughness can be characterized by the shift of the reference fracture toughness temperature (ΔT_o). A hyperbolic tangent function is used to fit Charpy absorbed energy data.

Figure 1 represents a plot of the fracture toughness T_o versus Charpy T_{41J} shifts. There are 126 data points in the database. A linear regression (y=ax) gives the coefficient of proportionality of 1.04, or almost 1:1 fit. The correlation coefficient (r^2) is 0.82, a relatively high value.

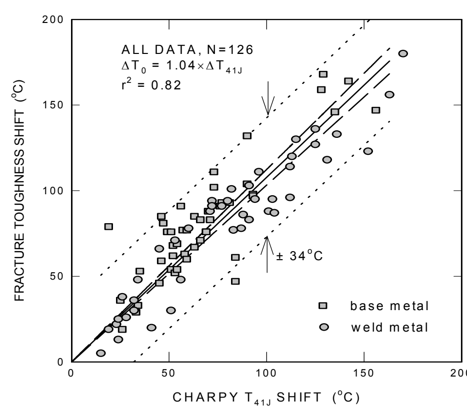

Fig 1. Correlation between fracture toughness T_o and Charpy T_{41J} shifts for RPV materials.

To compare the shifts of fracture toughness and Charpy curves due to irradiation, data sets of irradiated materials were grouped so that average values of neutron fluence of Charpy and fracture toughness data sets would be a match to each other. Although the values of neutron fluences were not always identical, it was assumed that the differences were negligible. This assumption is supported by the representation of the fluence factor in RG 1.99 [1], and especially since such differences were mostly observed at neutron fluences greater than 1×10^{19} neutrons/cm^2 (>1MeV) when the fluence factor starts to indicate a trend that is close to saturation.

In addition to the measured Charpy shifts, fracture toughness shifts from the present study are compared to the predicted radiation-induced shifts from the currently available procedures. All of the predictive equations are based on analyses of corresponding surveillance databases. However, all of these data are Charpy shifts. Thus, actual fracture toughness shifts from the current analysis could be compared with predictions based on Charpy data. Note that fracture toughness specimens were irradiated in test reactors. The comparison is made in terms of residuals $\Delta T_{41J\,(predicted)} - \Delta T_{o\,(measured)}$ vs. neutron fluence. In this case, any data point below zero would mean that the measured fracture toughness is higher than that predicted by an equation. The comparison is presented in Figs. 2 and 3.

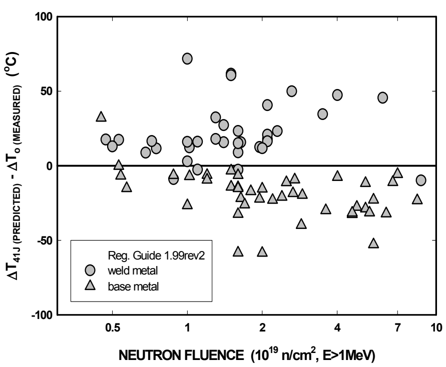

Fig. 2. Comparison of fracture toughness shifts with prediction of embrittlement based on Regulatory Guide1.99 Rev. 2 for weld and base metals.

The main observation is that none of the predictions provides enough conservatism for predicting fracture toughness shifts of base metals at neutron fluence above 1.5×10^{19} n/cm^2. It appears that the RG 1.99 predicts fracture toughness shifts of weld metals better than the base metal shifts. The newly developed EWO formula makes no such difference in predicting fracture toughness shifts between weld, plate, and forging materials. Nevertheless, even this formula tends to underestimate the fracture toughness shifts above 1.5×10^{19} n/cm^2. Predictions by the current revision of ASTM Standard E-900 provides comparison that is very similar to EWO formula prediction

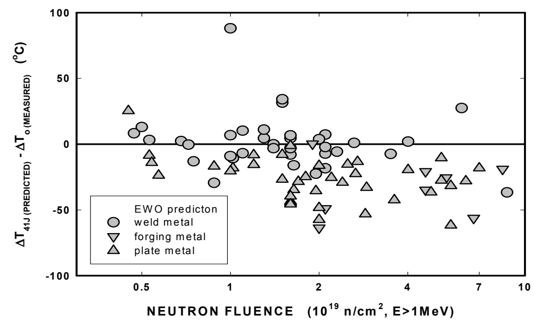

Fig. 3. Comparison of fracture toughness shifts with prediction of embrittlement based on Eason, Wright, Odette formula for weld, plate, and forging metals.

SUMMARY AND CONCLUSIONS

A database was assembled from information in the literature regarding radiation-induced shifts of static fracture toughness and Charpy impact toughness. Analysis shows that the master curve that the master curve methodology models well both the scatter of fracture toughness data and the temperature dependence of fracture toughness in both unirradiated and irradiated conditions. Fracture toughness shifts were compared with Charpy impact toughness shifts and it was shown that, on average, the Charpy transition temperature shift at 41J is about the same as the fracture toughness. The coefficient of proportionality is equal to 1.04. The RG 1.99, EWO, and the current revision of ASTM Standard E-900 predictive equations tend to underestimate fracture toughness shift at neutron fluence above 1.5×10^{19} n/cm^2.

REFERENCES:

[1]. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.99, rev. 2, “Radiation Embrittlement of Reactor Vessel Materials,” May 1998.

[2]. E.D. Eason, J.E. Wright, and G.R. Odette, Improved Embrittlement Correlations for Reactor Pressure Vessel Steels, NUREG/CR-6551. Modeling and Computing Services, 1998.