EFFECT OF THERMAL ANNEALING AND REIRRADIATION ON TOUGHNESS OF REACTOR PRESSURE VESSEL STEELS*

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ABSTRACT

One of the options to mitigate the effects of irradiation on reactor pressure vessels (RPVs) is to thermally anneal them to restore the toughness properties that have been degraded by neutron irradiation. Even though a post-irradiation anneal may be deemed successful, a critical aspect of continued RPV operation is the rate of embrittlement upon reirradiation. Various factors are known to affect the irradiated, annealed, and reirradiated toughness behavior of RPV steels, among which are postweld heat treatment, Cu, P, Ni content, and annealing temperature. The research conducted by the Heavy-Section Steel Irradiation (HSSI) Program at Oak Ridge National Laboratory, sponsored by the U.S. Nuclear Regulatory Commission, is investigating the fracture toughness response to annealing and, in particular, to subsequent reirradiation, as well as correlating toughness to properties determined by Charpy testing. This research is carried out on materials which were well characterized within different HSSI Irradiation Series, namely, high-copper and low upper-shelf Welds 61W through 67W from the Second and Third Irradiation Series, Heavy-Section Steel Technology (HSST) Program Plate 02 from the Fourth Irradiation Series, high-copper HSSI Weld 73W from the Fifth and Sixth Irradiation Series, and the high-copper low upper-shelf Midland Reactor beltline and nozzle course welds from the Tenth Irradiation Series. Materials were annealed in the temperature range from 343 to 482EC (annealing time varied between 1 and 14 days) after different dose of neutron exposure.

The available results show that annealing has resulted in various degrees of recovery of the mechanical properties that depend strongly upon the annealing temperature and to somewhat lesser degree upon the annealing time. For example, annealing at 454EC for 24 h recovers about two-thirds of the transition temperature shift caused by the neutron irradiation. Although annealing for longer times increases the recovery, it recovers at a decreasing rate. According to the present data, the annealing temperature of 454EC is high enough to provide nearly complete recoveries of the transition temperatures even after irradiation to very high fluences. It was noticed, however, that the post-anneal residual shift of transition temperature increases with increase in neutron fluence for the 343EC annealing temperature.

Recoveries of the Charpy upper-shelf energy (USE), fracture toughness J_{Ic} and tearing modulus appear to be more rapid and more extensive compared to recoveries of the Charpy and fracture toughness transition temperatures, which indicates different mechanisms for degradation of these properties upon irradiation. At the annealing temperature of 454EC, the Charpy USE and the fracture toughness J_{Ic} rise above the unirradiated level. Additionally, it was observed that the various Charpy toughness parameters react differently on annealing at 454EC. Among the three Charpy toughness parameters, absorbed energy appears to recover the most, lateral expansion the least, and percent shear is somewhat in between in the transition range.

Small-angle neutron scattering (SANS) studies of HSSI Weld 73W and Midland welds in the irradiated and irradiated/annealed conditions showed a large number of very fine copper-rich precipitates in the irradiated welds. Annealing at 454EC results in a significant drop of the number density and volume fraction of precipitates. However, it was found that annealing results in an increase in the radii of these precipitates; thus, annealing

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coarsens the copper-rich precipitates. As a result of these observations, it was concluded that the irradiated/annealed high-copper material had less copper in solution than before irradiation; therefore, the reembrittlement should be less that it was in the primary irradiation cycle. From a radiation sensitivity point of view, the irradiated/annealed material is microstructurally different than it was before irradiation.

A very limited reirradiation study shows that the reembrittlement rates for both HSST Plate 02 and HSSI Weld 73W are conservative relative to the "lateral shift" method for reembrittlement prediction, which supports the conclusions based on SANS measurements.