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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 fracture toughness properties that have been degraded by neutron irradiation. This paper summarizes experimental results of work performed at the Oak Ridge National Laboratory (ORNL) to study the annealing response of several irradiated RPV steels.

INTRODUCTION

Some early nuclear RPVs fabricated from certain types of steels may not meet the regulatory requirements for fracture toughness as they near their end of life. These regulatory requirements are promulgated in Appendix G of "Title 10," Part 50 of the *Code of Federal Regulations* (10CFR50) [1]. It is believed that in the next decade or so, several vessels may exceed the limits set by the pressurized thermal shock reference temperature (10CFR50.61). In that case, thermal annealing of the RPV may mitigate the effects of neutron embrittlement on fracture toughness. A dozen or so RPVs have already been thermally annealed in Eastern Europe [2] and a U.S. utility is contemplating annealing an RPV.

The U.S. Nuclear Regulatory Commission (NRC) amended 10CFR50 to include the "Thermal Annealing Rule," which provides new requirements for thermal annealing an RPV to mitigate the effects of neutron irradiation (10CFR50.66). The rule states that "two items of particular importance to the overall annealing are the recovery of fracture toughness and the rate of reembrittlement of the RPV beltline materials." These two items form the principal objectives of research performed at ORNL. Several RPV materials that are most likely to be annealed are being investigated, and their fracture toughness recovery and the reembrittlement rate of the fracture toughness will be correlated to the corresponding rates of the Charpy V-notch (CVN) specimen recovery and reembrittlement. The rate of reembrittlement is an important consideration since it will determine how long the plant may be safely operated after the RPV is annealed.

MATERIALS, ANNEALING TEMPERATURES, AND TIMES INVESTIGATED

The commercially fabricated submerged arc-welds and plate used in this study are commonly used in RPVs. These materials have been extensively characterized in their unirradiated and irradiated conditions [3][4][5]. The Heavy-Section Steel Irradiation (HSSI) Program weld 73W CVN specimens were irradiated to average exposures of 1.5 to 1.8×10^{19} n/cm^2 (>1 MeV). The irradiation was performed in the Oak Ridge Research Reactor for 1450 h at an average flux of 3×10^{12} n/(cm^2-s) (>1 MeV). The rest of the materials were irradiated for 3596 h at an average flux of 8×10^{11} n/(cm^2-s) (>1 MeV) to an average fluence of 1×10^{19} n/cm^2 (>1 MeV) in the Ford Nuclear Reactor at the University of Michigan. For the range of fluences and fluxes of this study, the influence of fluence and flux on the percent recovery of CVN properties is probably of secondary importance compared to the effect of material chemistry, annealing temperature, and time. The nominal irradiation temperature for all materials was 288°C.

The irradiated specimens were annealed at 343 and 454°C (650 and 850°F). These two temperatures have been often investigated as approximate lower and upper bounds of probable annealing temperatures [6]. The 343°C temperature could be used for a wet anneal. This is considerably simpler to perform than a dry anneal at 454°C, since the reactor internals would not have to be removed. One annealing time of 168 h was investigated at 343°C. In the case of HSSI weld 73W, four annealing times varying from 1 day to 2 weeks (336 h) were investigated at 454°C. The rest of the materials were annealed at the two temperatures mentioned for 168 h.

RESULTS AND DISCUSSION

The recovery of CVN impact properties as a result of annealing is typically measured by the changes in values of the Charpy upper-shelf energy (USE) and the 41-J transition temperature (TT) and are defined below. The values of the USE and TT were calculated from a nonlinear regression fit of a hyperbolic tangent equation to the CVN impact energy results [7]. The percent recovery of the ΔTT_i and USE are referenced to the shift or drop, respectively, due to neutron irradiation. A 100% recovery would indicate that the values of TT_i and USE after annealing have fully recovered their unirradiated values. The percent recovery of the TT_i is defined as the ratio of the residual transition temperature shift after annealing to the shift due to irradiation, $\Delta TT_i = TT_i - TT_{unirr}$, or:

$$\%\ \text{Recovery}\ TT_{ia} = \frac{TT_i - TT_a}{TT_i - TT_{unirr}} \cdot 100\ , \qquad (1)$$

where TT is the transition temperature at the 41-J energy level for the condition indicated by outer subscript (irradiated = i, annealed = a, unirradiated = unirr, and irradiated and annealed = ia). The percent recovery of the USE is defined in an analogous manner to Eq. (1):

$$\% \text{ Recovery } USE_{ia} = \frac{USE_a - USE_i}{USE_{unirr} - USE_i} \cdot 100 \ . \qquad (2)$$

A representative test result from testing the undersize HSSI weld 73W CVN specimens is shown in Fig. 1, in which the impact energy is shown as a function of temperature. The symbols are the experimental results for each specimen tested, and the three curves shown are the least-squares mean fits of the hyperbolic tangent equation to the experimental results. Also shown are the drops in USE and ΔTT_i, as well as the recoveries computed from Eqs. (1) and (2). The values used in either equation are those calculated from the mean curves. More details of the results of testing the undersize specimens from HSSI weld 73W may be found elsewhere [7].

In the case of toughness testing in the transition temperature range, the following relationship between the median fracture toughness in the transition region, $K_{Jc(med)}$, and temperature is used:

$$K_{Jc(med)} = 30 + 70 \exp\left[0.019(T-T_0)\right] , \qquad (3)$$

where T_0 is a parameter which, together with $K_{Jc(med)}$, is obtained using procedures that are in the process of being developed into an American Society for Testing and Materials standard, Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range [8][9]. The differences between the respective T_0s are used as measures of the effect of annealing. A typical result from such testing is shown in Fig. 2, which shows three $K_{Jc(med)}$ curves for the unirradiated, irradiated, and annealed conditions. Detailed results have been published [10][11].

The percent recovery of the Charpy ΔTT_i is plotted in Fig. 3. The figure shows that in general, the values of TT_i and the percent recovery depend strongly on the annealing temperature and material, and to a lesser degree on annealing time. This trend is illustrated by the annealing behavior of the specimens from HSSI weld 73W that has a recovery of TT_i that is insignificant for annealing at 343°C for 168 h, but is over 90% when annealed at 454°C for the same length of time. Increasing the annealing times from 96 to 168 to 336 h did not cause an appreciable gain in recovery. However, the degrees of recovery of the Midland weld and Heavy-Section Steel Technology Program Plate 02 materials due to annealing at 343°C for 168 h were approximately 49 and 36%, respectively, which is substantially greater than the 10% of the specimens for HSSI weld 73W. Thus, 343°C could be a viable annealing temperature for some materials.

The response of the USE to annealing, Fig. 4, is different than that of the TT_i in the following aspects. The percent recovery of the USE is substantial for all conditions investigated, and, in many cases, the USE overrecovers to values greater than the unirradiated value. Even for the 343°C/168-h anneal, the materials that experienced a substantial recovery in TT_i also recovered over 100% of the drop in USE due to irradiation. Although the mechanisms involved

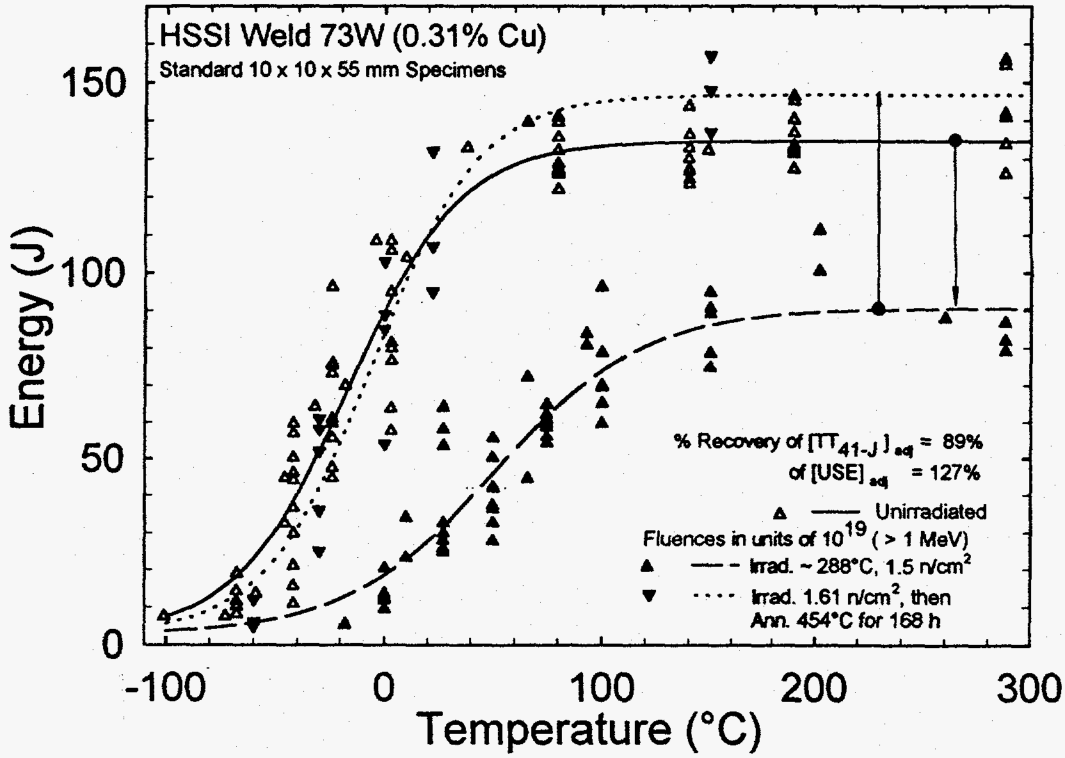

Fig. 1. Charpy energy of HSSI weld 73W in the unirradiated, irradiated, and annealed conditions. The irradiated specimens were annealed at 454°C for 168 h. An adjustment was made for the difference in fluence between irradiated and irradiated/annealed specimens.

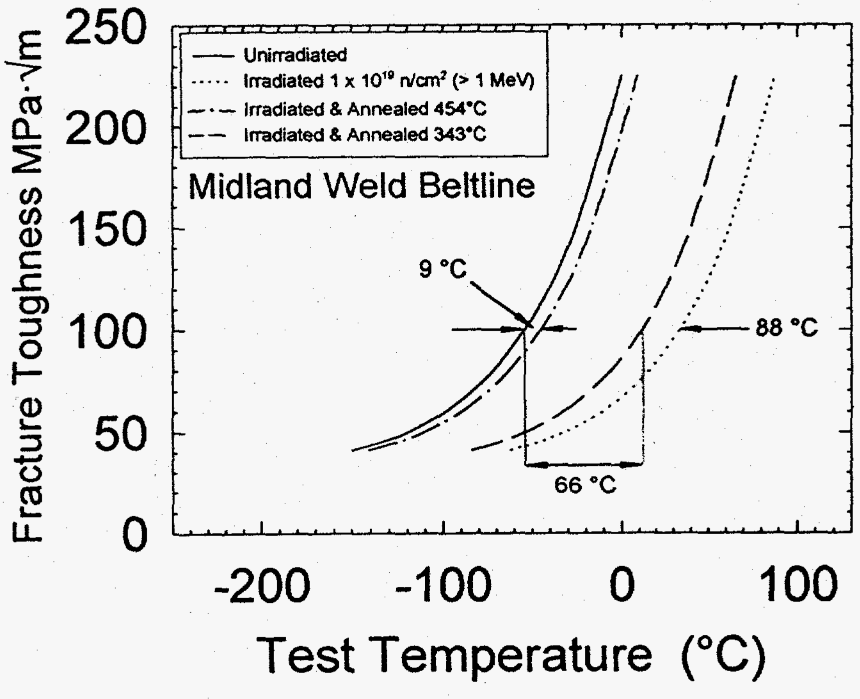

Fig. 2. Median fracture toughness of Midland beltline weld in the unirradiated, irradiated, and irradiated and annealed conditions. The irradiated specimens were annealed at 343 and 454°C for 168 h.

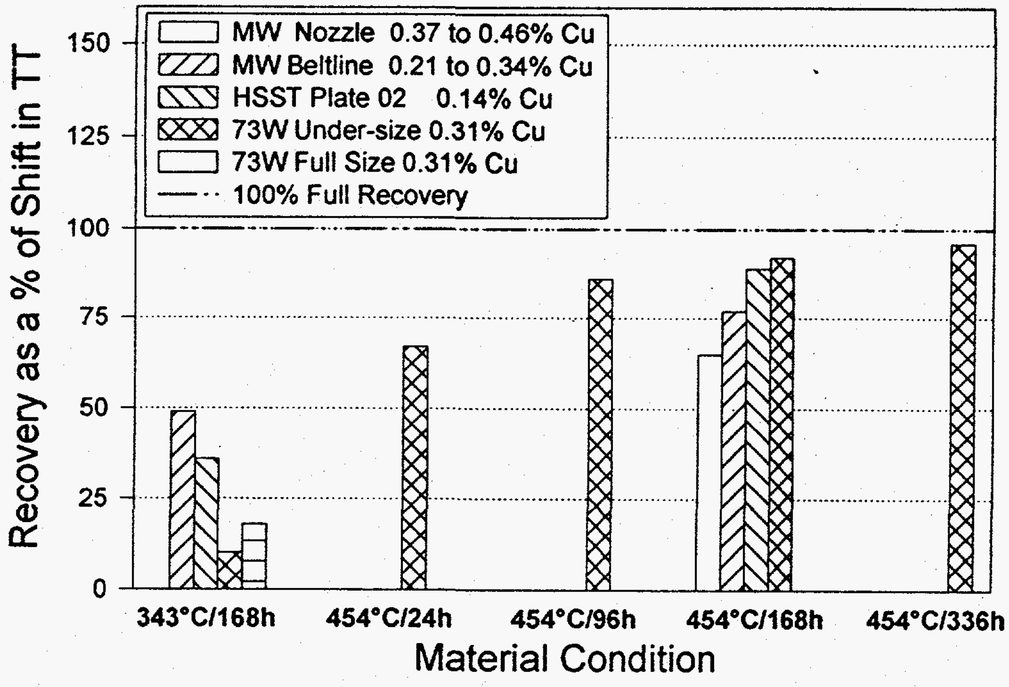

Fig. 3. Percent recovery of the Charpy transition temperature shift due to annealing.

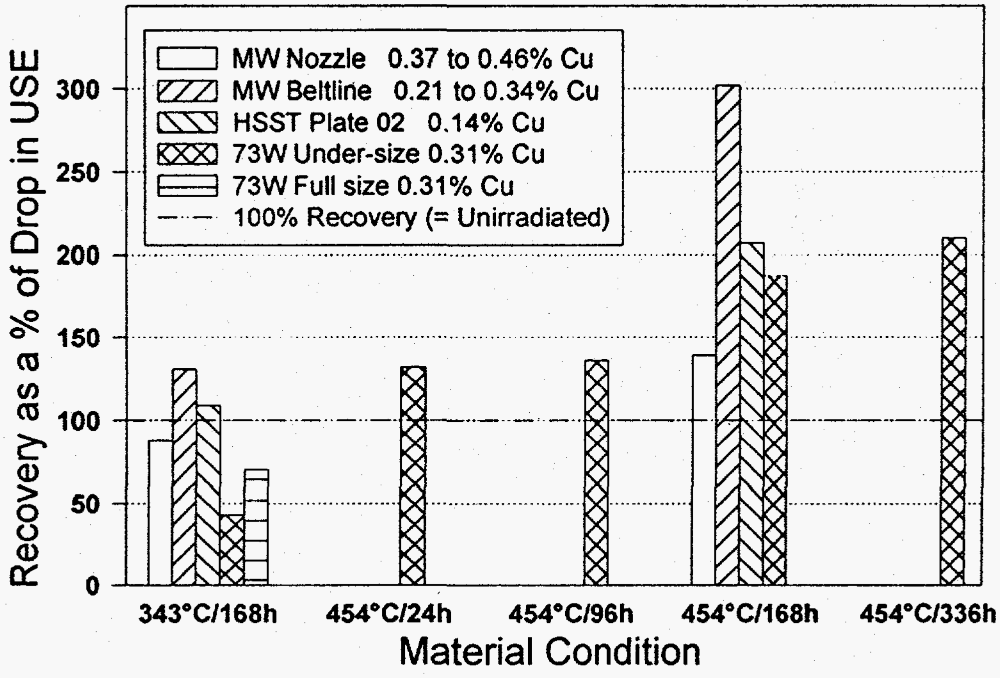

Fig. 4. Recovery as a percentage of Charpy drop in upper-shelf energy for the various materials tested in the unirradiated, irradiated, and irradiated and annealed conditions.

in the recovery of the USE and TT_i may be different, such a response suggests that there may be a relationship between the two.

Preliminary fracture toughness results from testing compact and precracked Charpy specimens of irradiated RPV steels annealed at 454°C for 168 h show similar trends as those obtained in testing CVN impact specimens [10][11]. Recovery depends strongly upon annealing temperature and the measure of fracture toughness. For most of the materials tested in the HSSI Program, although the recovery of the cleavage fracture toughness in the transition region as indicated by the T_0 temperature is partial, the tearing modulus and the ductile fracture toughness as indicated by J_{Ic} have either fully recovered or overrecovered. The investigation of the relationship between recovery of the fracture toughness and that of the CVN properties is still ongoing.

CONCLUSIONS

Specimens from irradiated submerged-arc welds and a plate material were annealed at two temperatures for various lengths of time. The following conclusions could be deduced from the results:

Annealing has resulted in various degrees of recovery of the transition temperature and USE that depend strongly upon the annealing temperature and to a somewhat lesser degree upon the annealing time.

Recovery at the lower annealing temperature investigated, 343°C and for the 168-h annealing time, has resulted in recovering most of the USE, but the recovery of the $TT_{41\text{-}J}$ varied from insignificant to substantial, depending upon the material.

The percentage recovery of the USE was always greater than the percentage recovery of the Charpy TT. For the materials investigated, there appears to be a relationship between the recovery of the $TT_{41\text{-}J}$ and the recovery of the USE, in that the materials that recovered a substantial portion of the $TT_{41\text{-}J}$ also recovered the USE to a significant degree. Thus, it appears that if the transition temperature recovers, this indicates a high likelihood that the USE will also recover to a significant degree.

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