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Comparisons of Irradiation-Induced Shifts in Fracture Toughness, Crack Arrest Toughness, and Charpy Impact Energy In High-Copper Welds

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ABSTRACT

The Heavy-Section Steel Irradiation (HSSI) Program is examining relative shifts and changes in shape of fracture and crack-arrest toughness versus temperature behavior for two high-copper welds. Fracture toughness 100-MPa$\sqrt{m}$ temperature shifts are greater than Charpy 41-J shifts for both welds. Mean curve fits to the fracture toughness data provide mixed results regarding curve shape changes, but curves constructed as lower boundaries indicate lower slopes. Preliminary crack-arrest toughness results indicate that shifts of lower-bound curves are approximately the same as CVN 41-J shifts with no shape changes.

1 INTRODUCTION

Fracture mechanics integrity analyses of reactor pressure vessels (RPVs) often use the initiation and arrest fracture toughness curves of Sect. XI of the *ASME Boiler and Pressure Vessel Code.* Effects of neutron irradiation on toughness are accounted for by shifting the curves without change in shape by the shifts (plus a margin) of Charpy V-notch (CVN) impact energy curves at the 41-J level. Implied is that shifts in fracture toughness curves are the same as those of the CVN 41-J energy level, and that irradiation does not change their shapes. The Fifth and Sixth HSSI Irradiation Series are determining K_{Ic} and K_{Ia} curve shifts and shapes for two irradiated high-copper, 0.23 and 0.31 wt %, submerged-arc welds (72W and 73W, respectively). Irradiations were performed at a nominal temperature of 288°C to average fluences of about 1.5×10^{19} neutrons/cm^2 (>1 MeV) for fracture toughness and impact specimens and about 1.9×10^{19} neutrons/cm^2 (>1 MeV) for crack arrest specimens. Compact specimens up to 203 and 102-mm and compact crack arrest specimens up to 51 and 33-mm thickness were tested, in unirradiated and irradiated conditions, respectively. All tests except a few irradiated crack arrest tests have been completed and presented previously[1,2]. The 41-J CVN shifts were 72 and 82°C, while the 68-J shifts were 82 and 105°C for welds 72W and 73W, respectively.

2 FRACTURE DATA EXAMINATION AND ANALYSIS

The first step to evaluate the fracture toughness data was to establish the data base appropriate for statistical analyses. For those specimens which met the E 399

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criteria for a valid K_{Ic}, the K_{Ic} value is used. For those specimens which exhibited curvature in the load-displacement record, indicative of plastic deformation and, perhaps, stable ductile tearing, the K_{Jc} value at cleavage was used. Because the data base includes results from both linear-elastic and elastic-plastic fracture mechanics calculations, toughness data are designated K_{cl} for cleavage fracture toughness. Numerous cleavage pop-ins occurred in the irradiated compact specimens, 28 out of 110, compared to only two out of 156 unirradiated specimens. For previously stated reasons,[1] only initial pop-ins were used to determine cleavage fracture toughness and pop-ins of any size representing cleavage events in the specimens were considered significant.

The fitted exponential curve from Ref. 3 (EPRI curve) is widely used to approximate the K_{Ic} curve in Sect. XI of the ASME Code[4] and is used herein for comparison and to develop a lower boundary to the fracture toughness data. Mean fracture toughness 100-MPa√m temperature shifts are about 83 and 99°C for 72W and 73W, respectively. For combined K_{cl} data sets vs T - RT_{NDT}, the mean curve for the irradiated data is displaced upward in temperature because the fracture toughness shifts are greater than the CVN 41-J shifts. At K_{cl} values of 50, 100, and 200 MPa√m, differences are about 10, 15, and 17°C. The standard deviation associated with the difference at 100 MPa√m is 13.7°C, a large value relative to the difference observed. The increasing temperature offset between the two curves with increasing K_{cl} reflects the average change in curve shape. The 7°C average increase between the normalized unirradiated and irradiated curves from 50 to 200 MPa√m corresponds to 5.3 and 8.6°C, for 72W and 73W respectively, indicating a greater change in slope for the higher copper weld.

Figure 1 shows a plot of the irradiated fracture toughness data and various curves for 73W. The EPRI curve is shown for the unirradiated condition. The dashed curves labeled 1 through 3 represent different methods for shifting the EPRI curve. The curve labeled 4 represents the ASME K_{Ia} curve shifted upward in temperature by the Charpy 41-J shift (ΔTT_{41}). The curve labeled 5 is the 5 percentile curve produced using Wallin's method.[5] For 72W, the data are bounded by the ΔTT_{41}+ Margin curve and the ΔK_{cl} curve, but neither of those curves quite bound all the data for 73W. The margin is 15.6°C as defined in *Regulatory Guide 1.99* (Rev. 2) assuming credible surveillance data. It is important to recognize that the margin is derived from analyses of CVN surveillance results and it not meant to be representative of fracture toughness data as such. Nonetheless the observation that the margin is fully consumed due to the inconsistency of fracture toughness and CVN shifts, leaving nothing to cover other uncertainties, is profoundly disturbing. The K_{Ia} curve is shown for comparison with the shifted EPRI curves, especially regarding curve shape since the irradiated K_{cl} curves for these two welds appear to exhibit some shape change after irradiation. Figure 2 shows a plot of all irradiated fracture toughness data vs T - RT_{NDT}. The RT_{NDT} for each weld is defined as the unirradiated RT_{NDT} plus ΔTT_{41}. Eight data points fall below the EPRI curve. The dashed curve is the EPRI curve shifted upward in temperature to bound the data; a shift of 18°C is required.

In contrast to the fracture toughness data, crack arrest data indicate shifts of lower bound curves for both welds approximately equal ΔTT_{41} (Fig. 3). Moreover, the ASME K_{Ia} curve, when shifted by ΔTT_{41}, normalized for fluence, is a conservative estimate of irradiated crack-arrest toughness. The shapes of the lower bounding curves do not seem altered by irradiation. Unirradiated and irradiated crack-arrest toughness (K_a) data have been plotted vs T - RT_{NDT} in Fig. 4. All K_a data sets form a consistent trend when indexed to their respective RT_{NDT}s. The ASME curve is a conservative estimate of their lower bound. At temperatures below RT_{NDT}, the toughness margin between the lower-bound and

ASME K_{Ia} curves decreases. The lower-bound curve, shown as dotted in Fig. 4, is the ASME K_{Ia} curve shifted downward in temperature until the first data point is encountered. The 28°C shift thus obtained was for both the irradiated 72W and unirradiated 73W weld. Therefore no trend can yet be established as a function of irradiation exposure. More experimental data may alter this lower bound. The statistical evaluation of the K_a data is ongoing. Planned testing of 20 additional irradiated K_a specimens should substantially augment the data base.

3 DISCUSSION

Fracture toughness values from small cleavage pop-ins suggest that pop-ins observed in this study are significant and indicate propensity for cleavage fracture in test specimens. Statistical analyses and curve fitting showed that irradiation-induced temperature shifts at a fracture toughness of 100 MPa$\sqrt{m}$ were greater than those at a Charpy energy of 41 J, but agree well with the Charpy 68-J transition shifts. That 68-J temperature shifts are greater than 41-J shifts reflects the change in the slope of the CVN curves following irradiation. Linearized two-parameter Weibull fits indicate some decrease in mean slopes, but they are not statistically significant. Curves constructed to bound all data do indicate a substantial slope decrease, especially for weld 73W. Because the EPRI curve is a lower-bound curve, this latter observation is important. The five percentile curve from the Wallin procedure bounds all the data, but has a substantially lower slope than the EPRI curve and appears to be overly conservative at fracture toughness levels above about 100 MPa$\sqrt{m}$. Curve shape changes can be accounted for by simply applying large enough shifts, but to do so raises concerns of accuracy. Data in the present case indicate that the EPRI curve shifted by ΔTT_{41} plus margin would not have bounded a larger data base, and more margin adjustment is needed, but would result in overconservatism in the lower transition region. Therefore, shallower curves such as the five percentile curve of Wallin or the K_{Ia} curve deserve consideration.

Preliminary observations from the K_a testing indicate no irradiation-induced curve shape changes. Perhaps then, the K_{Ia} curve shape could describe irradiated K_{Ic} behavior for materials which exhibit irradiation-induced toughness shifts above some prescribed amount. A comparison of the EPRI and K_{Ia} curves as well as the bounding curves for the combined irradiated data vs $T - RT_{NDT}$ (Fig. 5) shows that the K_{cl} curve has been shifted to higher temperatures than the K_a curve. An argument can be made that, because irradiation hardening increases yield strength, strain-rate sensitivity is reduced such that quasi-static K_{Ic} values tend toward agreement with dynamic K_{Id} and K_{Ia} values. This does not, of course, allow for the results shown in Fig. 5. One important factor is the number of tests performed; 110 fracture toughness results but only 34 crack-arrest results. Further, fracture toughness and crack-arrest toughness data for the unirradiated welds are not nearly as far apart as the ASME curves. By not considering pop-ins in irradiated fracture toughness data, the K_{cl} and K_a bounding curves would be very close. Resolution of the observations in Fig. 5 most likely resides in consideration of statistical variations.

CONCLUSIONS

Extensive fracture and crack arrest toughness testing on high-copper welds have shown that both mean and lower bound irradiation-induced shifts in K_a agree well with ΔTT_{41} whereas those of K_{cl} are greater. Changes in shape of the mean K_{cl} vs temperature behavior could not be verified statistically but a decrease in slope was found in its lower bound.

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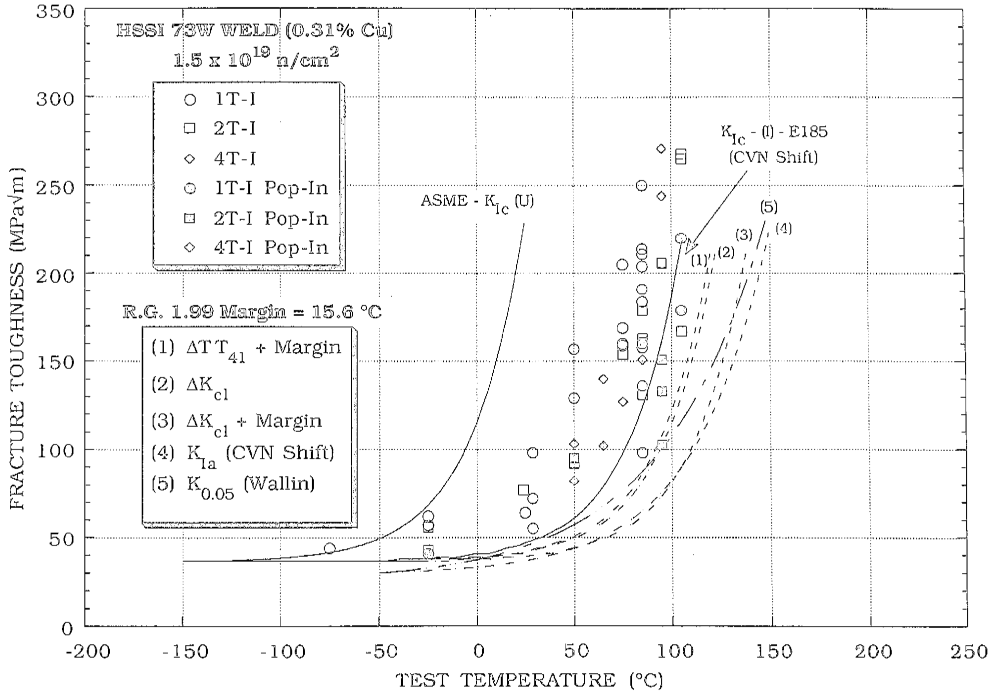

Fig. 1. Fracture toughness, K_{cl}, vs test temperature. The ASME K_{Ic} curve is for unirradiated data. Curves labeled 1, 2, and 3 represent the ASME curve shifted by indicated criteria. The ASME K_{Ia} curve is shifted by ΔTT_{41}. The $K_{0.05}$ curve is the five percentile curve for all data combined using the Wallin procedure.

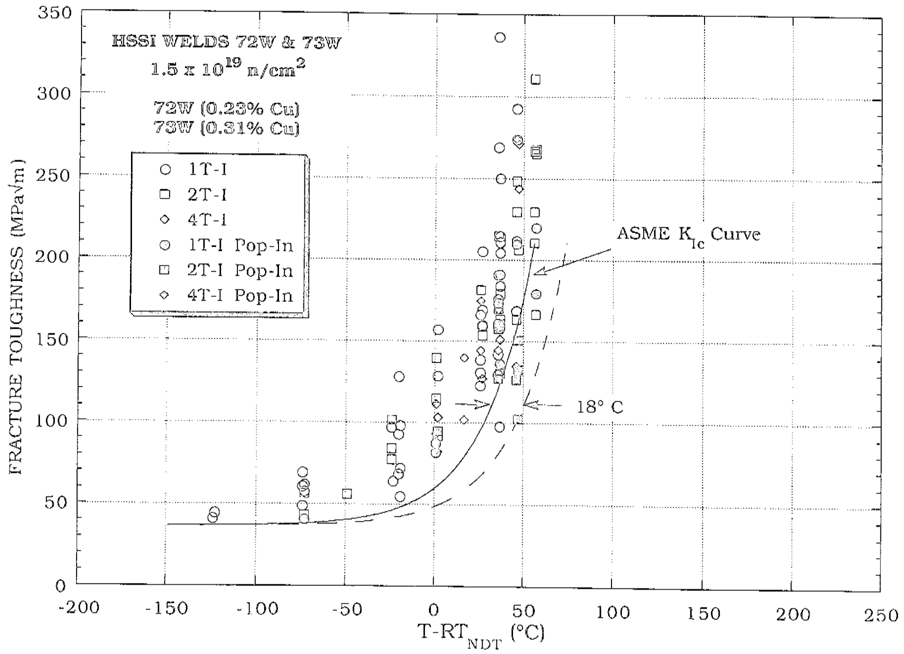

Fig. 2. Fracture toughness, K_{cl}, vs T - RT_{NDT}. Dashed ASME curve is shifted an additional 18°C to just bound irradiated data.

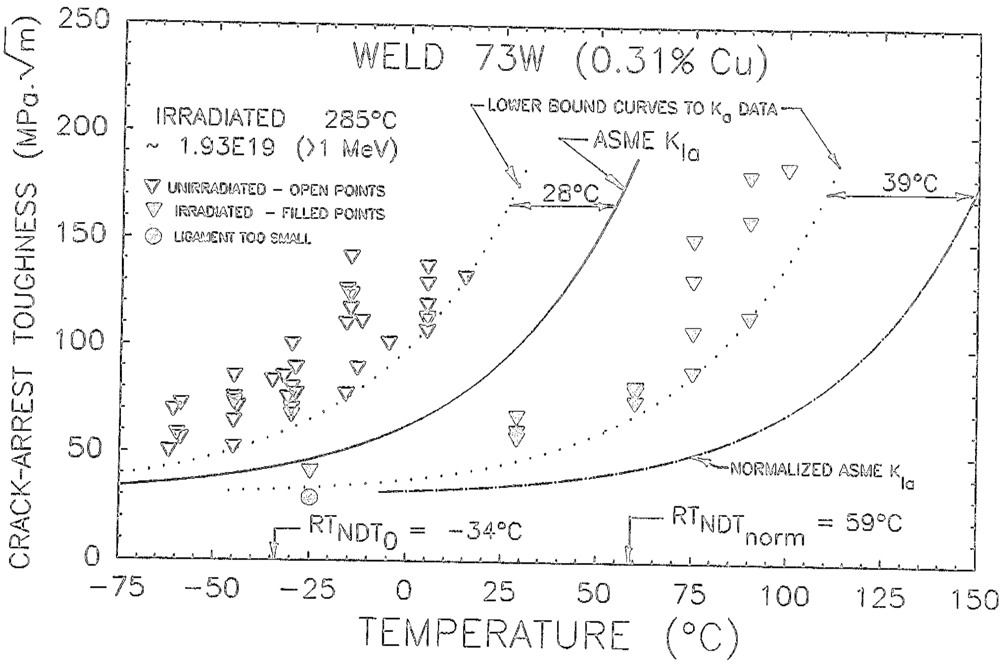

Fig. 3. Crack-arrest toughness, K_a, vs temperature. Dotted curves are lower bounds to the data.

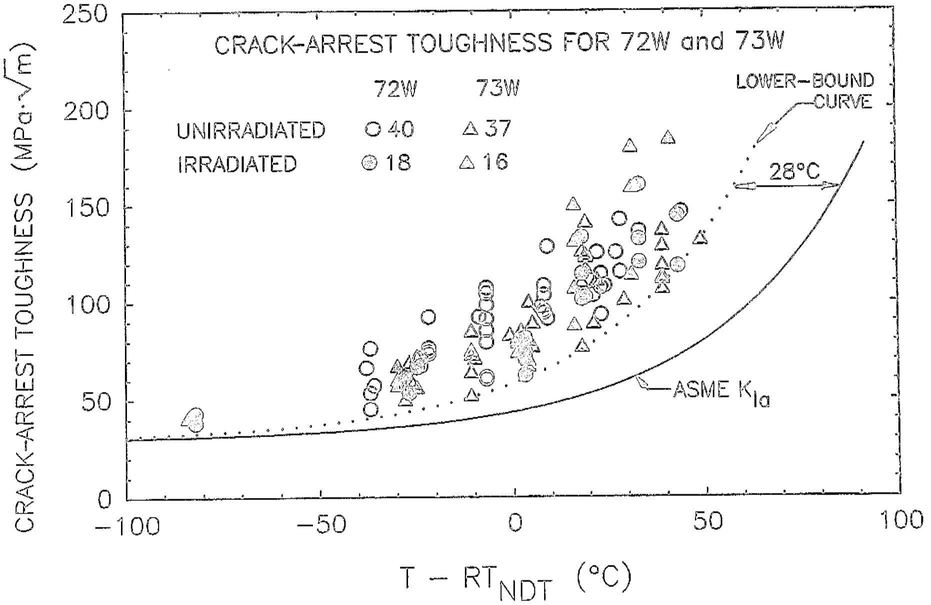

Fig. 4. Crack-arrest toughness, K_a, vs T - RT_{NDT}. The number of results plotted are given beside each plot symbol in the legend.

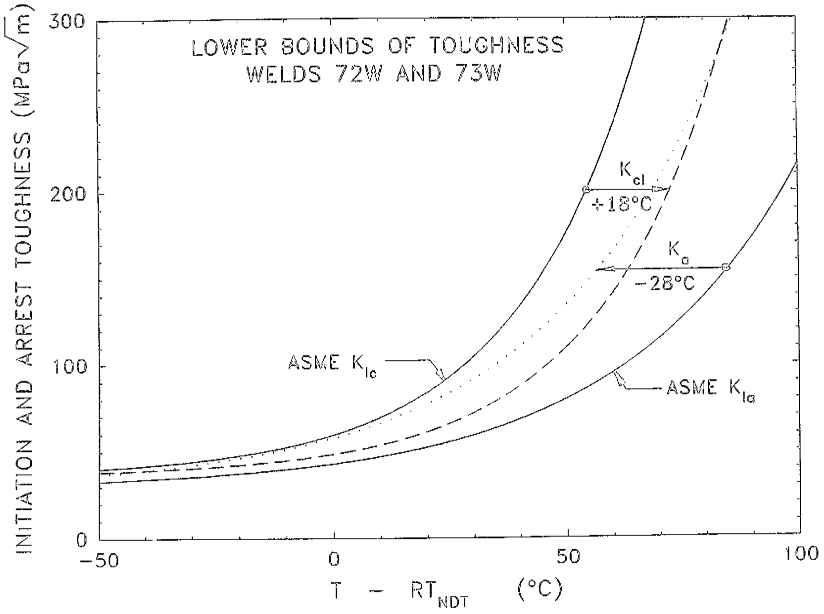

Fig. 5. Bounding fracture toughness, K_{cl}, and crack-arrest toughness, K_a, vs T - RT_{NDT}. ASME K_{Ic} and K_{Ia} curves show that the bound of K_{cl} data falls at higher temperatures than that for K_a data.