**Proceedings of the ASME 2022
Pressure Vessel and Piping Conference
PVP2022
July 17-22, Las Vegas, NV, USA**

PVP2022-84827

USE OF MINI-CT SPECIMENS FOR FRACTURE TOUGHNESS CHARACTERIZATION OF IRRADIATED HIGHLY EMBRITTLED WELD[i]

Mikhail A. Sokolov[1]

Oak Ridge National Laboratory, Oak Ridge, TN

[1] Contact author: sokolovm@ornl.gov

ABSTRACT

In the 1990's, the Heavy Section Steel Irradiation Program at the ORNL performed investigation of the shape of the fracture toughness master curve for reactor pressure vessel steel highly embrittled because of irradiation exposure. A radiation-sensitive reactor pressure vessel (RPV) weld with intentionally enhanced copper content, designated KS-01, has been characterized in terms of static initiation (K_{Jc}) and Charpy impact toughness in the unirradiated and irradiated conditions. The objective of this original project was to investigate the ability of highly embrittled material to maintain the shape of the unirradiated transition fracture toughness curve, as well as to examine the ability of the Charpy 41-J shift to predict the fracture toughness shift at such high level of embrittlement. Irradiation of this weld was performed at the University of Michigan Ford Reactor in the new HSSI irradiation-anneal-reirradiation (IAR) facility. Broken specimens from that project have been saved in ORNL storage. To verify applicability of Mini-CT specimens for fracture toughness characterization of RPV materials as part of the DOE Light Water Reactor Sustainability Program, Mini-CT specimens were machined from broken Charpy specimens and tested according to ASTM E1921 standard. As result of this study, the fracture toughness of this weld derived by testing Mini-CT specimens in the unirradiated and irradiated conditions is compared to previously reported fracture toughness derived by large number of conventional specimens.

Keywords: Mini-CT, RPV, radiation embrittlement, fracture toughness

1. INTRODUCTION

Any fracture toughness specimen that can be made out of the broken halves of standard Charpy specimens may have exceptional utility for evaluation of reactor pressure vessels since it would allow one to determine and directly monitor the actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most used specimen geometry in surveillance programs. The advantage of the Mini-CT specimen technique is that it has the same cross-section (10x10 mm) as a standard Charpy specimen such that it can be made from the simple slice of a broken half of a Charpy specimen. Moreover, the thickness of this Mini-CT (slightly below 5 mm) is just large enough to fit the very narrow validity limit window allowed by ASTM E1921. The current ASTM E1921 validity limit is set up as:

$$K_{Jc(limit)} = \sqrt{\frac{E b_o \sigma_{YS}}{30(1-\vartheta^2)}} \quad (1)$$

where E is the elastic modulus, b_o is the remaining ligament, σ_{ys} is the yield strength, and υ is the Poisson ratio. Thus, for a typical reactor pressure vessel steel in the unirradiated condition with the reference transition temperature, T_0, of about -50°C and the yield strength at this temperature of about 520MPa, the $K_{Jc(limit)}$ to Mini-CT specimen is approximately 130MPa√m. Once it is size adjusted to 1T equivalence, it drops below 100MPa√m. For irradiated condition, the validity limit is slightly higher than in the unirradiated condition as material experience increase in yield strength as result of radiation hardening.

In this study, Mini-CT specimens were used to perform fracture toughness characterization of a highly radiation sensitive KS-01 weld. The weld, designated KS-01, has intentionally increased copper, nickel, and manganese contents. It was provided to ORNL by MPA-Stuttgart. Originally, this weld was used within a German irradiation research program, and it exhibited extremely high sensitivity to radiation and ORNL performed irradiation of this weld at the University Michigan Ford reactor at 288°C. In the previous ORNL irradiation study [1], tensile, Charpy impact, and various size fracture toughness specimens were irradiated at to 0.74×10^{19} n/cm^2. In this study, Mini-CT specimens were machined out of broken previously tested Charpy specimens. The irradiated broken Charpy specimens were machined into Mini-CT specimens at BWXT.

2. MATERIAL DESCRIPTION AND IRRADIATION HISTORY

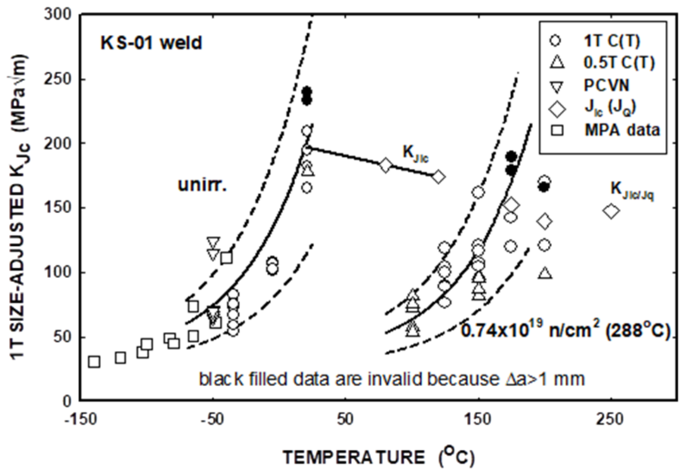


FIGURE 2: 1T SIZE-ADJUSTED FRACTURE TOUGHNESS DATA OF KS-01 WELD BEFORE AND AFTER IRRADIATION [1]

The KS-01 weld was offered to ORNL by MPA-Stuttgart in Germany based on the requirement that the material achieve a high embrittlement level after a relatively short test reactor irradiation. The weld has intentionally increased copper, nickel, and manganese contents (as seen in Table 1 provided by MPA-Stuttgart). Chromium content is also high relative to a typical U.S.-made RPV weld, but it is more common for German-made RPV welds. This weld was used within a German irradiation research program, and it exhibited extremely high sensitivity to radiation. MPA provided the weld together with mechanical properties in the unirradiated and irradiated conditions. Most of the data provided were Charpy impact and tensile properties before and after irradiation, although a limited amount of fracture toughness (linear-elastic K_{Ic}) data was also provided. Specimens were machined in the T-L orientation. In addition to fracture toughness specimens, standard Charpy V notch (CVN), tensile specimens, and coupons for atom probe characterization were included for irradiation.

TABLE 1. CHEMICAL COMPOSITION OF KS-01 WELD, WT%.

C	Ni	Mn	Mo	Cr	Cu	Si	P
0.006	1.23	1.64	0.70	0.47	0.37	0.18	0.017

The original irradiation was performed at the University of Michigan Ford Reactor at 288°C. The specimens were irradiated to 0.74×10^{19} neutron/cm^2 (E>1MeV). As expected, the KS-01 weld exhibited a large shift of transition temperature of 169°C and the USE decreased from 118 to 78 J. Charpy impact properties of KS-01 weld before and after irradiation are presented in Figure 1 [1]. In addition to a large shift of transition temperature and drop in the USE, this weld also exhibited a change in the slope of the transition curve typical for irradiated RPV materials. For example, the shift of T_{41J} was 169°C compared to 217°C shift of T_{68J}.

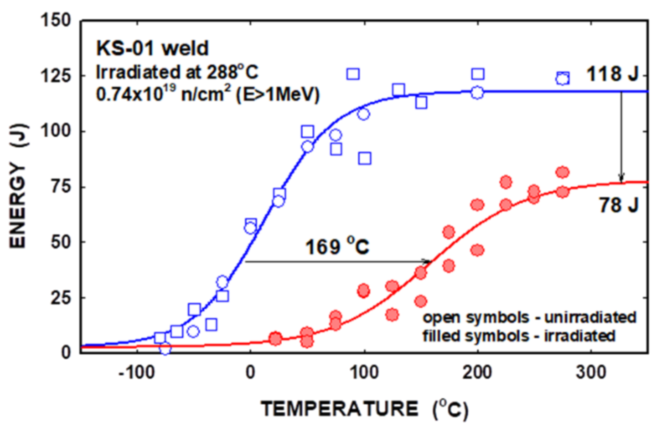


FIGURE 1: CHARPY IMPACT DATA OF KS-01 WELD IN THE UNIRRADIATED AND IRRADIATED CONDITIONS [1]

Fracture toughness data were generated using compact tension specimens of 0.5T and 1T sizes and precracked Charpy specimens (PCVN). Only 0.5T and 1T CT specimens were tested in the irradiated condition. Remarkably, the shift of the reference fracture toughness temperature was reported to be almost identical to the Charpy shift, 165°C, see Figure 2 [1].

3. RESULTS AND DISCUSSION

The Mini-CT specimens were machined from broken Charpy halves. The irradiated broken halves were retrieved from hot cell storage and sent to BWXT for machining. Figure 3 provides overall dimensions of the Mini-CT specimen used in this study. All specimens were fatigue precracked to the *a/W* (crack depth to width) value of approximately 0.5.

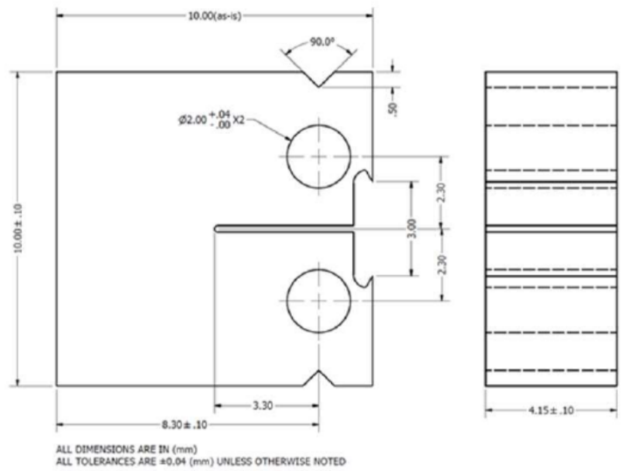


FIGURE 3: MINI-CT SPECIMEN USED IN THIS STUDY

The initial test temperatures were selected based on the data on Figure 2. The testing was performed under carefully controlled conditions in accordance with ASTM E1921 such that the values can be compared to the fracture toughness performance of previously tested large specimens. A total of 12 Mini-CT specimens have been tested in the unirradiated condition and 16 Mini-CT specimens have been tested in the irradiated condition. The data are summarized in Figure 4. All specimens cleaved; however, the three highest toughness irradiated specimens, two tested at 120°C and one tested at 145°C, cleaved after substantial stable crack growth and, thus, were censored according to ASTM E1921 procedure. This observation is similar to what was observed emphasized in low upper-shelf weld [2,3]. A visual comparison of the present Mini-CT and previous conventional specimens data in Figure 4 show good overall agreement between Mini-CT and conventional specimens data. Yet, Mini-CT data tend to produce higher reference fracture toughness temperatures than conventional large specimens.

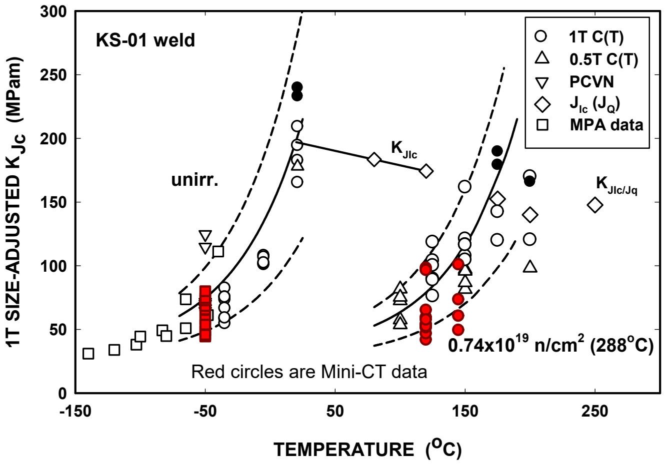


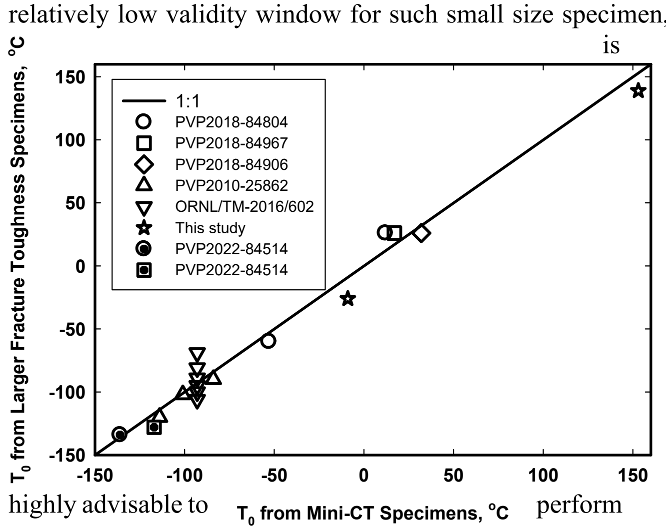
FIGURE 4: COMPARISON OF MINI-CT DATA FROM THE PRESENT STUDY VERSUS PREVIOUSLY REPORTED [1] LARGE CONVENTIONAL SPECIMENS

The reference fracture toughness temperature, T_0, derived from testing of Mini-CT specimens of KS-01 weld in the unirradiated condition is -9^{o}C compared to -26^{o}C reported for larger specimens [1]. The T_0 temperature derived from irradiated Mini-CT specimens is 153^{o}C compared to 139^{o}C reported for larger specimens [1]. Table 2 provides some summary of comparison of T_0 values derived from Mini-CT (MCT) specimens and corresponding T_0 values derived from larger fracture toughness (LFT) specimens. In addition to some published data, this Table includes results from characterization of KS-01 weld performed in this study. Figure 5 provides visual illustration of this comparison.

TABLE 2. COMPARISON OF T_0 DERIVED FROM MINI-CT SPECIMENS COMPERED TO T_0 DERIVED FOR LARGER FRACTURE TOUGHNESS SPECIMENS

Material	MCT T_0, ^{o}C	LFT T_0, ^{o}C	LFT Type	MCT - LFT, ^{o}C	Ref.
Midland Beltline Weld, UNIRR	-53	-60	PCVN, 0.5T, 1T,2T, 4T	7	[2]
Midland Beltline Weld, IRR	12	26	PCVN, 0.5T, 1T	-14	[2]
Midland Beltline Weld, IRR	17	26	PCVN, 0.5T, 1T	-9	[4]
Midland Beltline Weld, IRR	32	26	PCVN, 0.5T, 1T	6	[5]
SFVQ1A A508 Cl3	-101	-102	0.4T to 4T	1	[6]
SQV2A Heat 1, A533B1	-84	-90	0.4T to 4T	6	[6]
SQV2A Heat 2, A533B1	-114	-120	0.4T to 4T	6	[6]
HSST Plate 13B	-93	-69	1T	-24	[7]
HSST Plate 13B	-93	-81	1T SE_{Bx2B}	-12	[7]
HSST Plate 13B	-93	-89	1T SE_{BxB}	-4	[7]
HSST Plate 13B	-93	-95	0.4T	2	[7]
HSST Plate 13B	-93	-100	0.4T SE_{Bx2B}	7	[7]
HSST Plate 13B	-93	-106	0.4T PCVN	13	[7]
F82H	-136	-134	0.5T	-2	[8]
EUROFER97	-117	-128	0.5T	11	[8]
KS-01 Weld, UNIRR	-9	-26	PCVN, 0.5T, 1T	17	
KS-01 Weld, IRR	153	139	14	14	
AVERAGE				1	

Available data clearly indicate that, on average, small size Mini-CT specimens provide very good tool to characterize fracture toughness of RPV materials in both, the unirradiated and irradiated conditions. All researchers noted that because of relatively low validity window for such small size specimen, it is highly advisable to perform



testing of Mini-CT specimens approximately 30°C below expected T_0 value. Some researchers also indicated that low-upper shelf materials may present additional challenge and may require even lower test temperature for such material, see [2,3] for example.

FIGURE 5: COMPARISON OF T_0 DERIVED FROM MINI-CT SPECIMENS COMPERED TO T_0 DERIVED FOR LARGER FRACTURE TOUGHNESS SPECIMENS

4. SUMMARY

Overall, the T_0 value derived from a relatively small number of Mini-CT specimens in this study is in good agreement with the T_0 value from previously reported fracture toughness data generated using a much larger number of bigger, conventional fracture toughness specimens. The review of available data on the use of Mini-CT specimens for characterization of the fracture toughness of reactor pressure vessel steels revealed very good correspondence between T_0 derived from Mini-CT and larger fracture toughness specimens in both, the unirradiated and irradiated conditions. It is advisable to perform test of Mini-CT specimens in the temperature range ~30°C below anticipated T_0 value. Special precaution needs to be done when Mini-CT specimens are used to characterize low upper-shelf material.

ACKNOWLEDGEMENTS

This research was sponsored by the U.S. Department of Energy, Office of Fusion Energy Sciences, under contract DE-AC05-00OR22725 with UT-Battelle, LLC. The machining of irradiated Mini-CT specimens was assisted by Dr. M. Yamamoto from CRIEPI, who also provided deep insights on this study. The author thanks Drs. Xiang (Frank) Chen and Wei Tang for reviewing this paper. Help from Dr. Thomas Rosseel, Materials Research Program Manager for LWRSP, is highly appreciated.

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