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The Assessment and Validation of Mini-Compact Tension Test Specimen Geometry and Progress in Establishing Technique for Fracture Toughness Master Curves for Reactor Pressure Vessel Steels

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Light Water Reactor Sustainability Program

The Assessment and Validation of Mini-Compact Tension Test Specimen Geometry and Progress in Establishing Technique for Fracture Toughness Master Curves for Reactor Pressure Vessel Steels

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EXECUTIVE SUMMARY

Small specimens are playing the key role in evaluating properties of irradiated materials. The use of small specimens provides several advantages. Typically, only a small volume of material can be irradiated in a reactor at desirable conditions in terms of temperature, neutron flux, and neutron dose. A small volume of irradiated material may also allow for easier handling of specimens. Smaller specimens reduce the amount of radioactive material, minimizing personnel exposures and waste disposal. However, use of small specimens imposes a variety of challenges as well. These challenges are associated with proper accounting for size effects and transferability of small specimen data to the real structures of interest.

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 (RPVs) since it would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs.

Assessment and validation of the mini-CT specimen geometry has been performed on previously well characterized HSST Plate 13B, an A533B class 1 steel. It was shown that the fracture toughness transition temperature measured by these Mini-CT specimens is within the range of T_0 values that were derived from various larger fracture toughness specimens. Moreover, the scatter of the fracture toughness values measured by Mini-CT specimens perfectly follows the Weibull distribution function providing additional proof for validation of this geometry for the Master Curve evaluation of rector pressure vessel steels. Lastly, an International collaborative program has been established to extend the assessment and validation efforts to irradiated weld metal. The program is underway and involves ORNL, CRIEPI, and EPRI. It is anticipated that results of this international program will be reported in FY2017.

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1. INTRODUCTION

Small specimens are playing the key role in evaluating properties of irradiated materials. The use of small specimens provides several advantages. Typically, only a small volume of material can be irradiated in a reactor at desirable conditions in terms of temperature, neutron flux, and neutron dose. A small volume of irradiated material may also allow for easier handling of specimens. Smaller specimens reduce the amount of radioactive material, minimizing personnel exposures and waste disposal. However, use of small specimens imposes a variety of challenges as well. These challenges are associated with proper accounting for size effects and transferability of small specimen data to the real structures of interest.

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 (RPVs) since it would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs.

A few years ago, the Central Research Institute of Electric Power Industry (CRIEPI) had developed the test technique for the miniature compact tension [C(T)] specimens (Mini-CT), whose dimensions are approximately 4 x 10 x 10 mm. A round robin program had been organized with the participation of Japanese and International academia, industries and government institutes, including ORNL. The round robin program aimed to verify the reliability and robustness of experimental data of the Mini-CT among different laboratories. The ORNL results for the Mini-CT round robin contribution are summarized in [1]. It was shown that this Mini-CT specimens were offering a very attractive opportunity to derive the same fracture toughness transition temperature values, T_o, as those derived by larger fracture toughness specimens. Yet, the advantage of this Mini-CT specimen technique is that multiple specimens can be machined from one half of a broken Charpy specimen, used in a standard surveillance capsule of a reactor pressure vessel.

Based on the outcome of the ORNL contribution to the international round robin program [1], it was decided to extend such research to provide further assessment and validation of the Mini-CT test specimen geometry using a typical US reactor pressure vessel steels. A three steps plan has been adopted to address these needs. The first phase was aimed at performing fracture toughness characterization of a typical US reactor pressure vessel steel for which a very well characterized database has been already established by using various types of fracture toughness specimens larger than Mini-CT. The second phase should address the applicability of Mini-CT specimens for a typical reactor pressure vessel weld material. The final step would be validation of the Mini-CT specimen for irradiated material.

This report summarizes the results of the first phase of assessment and validation of Mini-CT test specimen geometry using typical US reactor pressure vessel steel performed at ORNL. The report is prepared in satisfaction of Milestone M3LW-16OR0402014 – "Complete report providing the assessment and validation of mini-Compact Tension test specimen geometry and progress in establishing technique for fracture toughness Master Curves for reactor pressure vessel steels."

2. ASSESSMENT AND VALIDATION OF MINI-CT TEST SPECIMEN GEOMETRY USING HSST A533B PLATE 13B

The HSST Plate 13B has been selected for assessment and validation of Mini-CT tests specimen geometry based on a previously generated large database using various large-scale fracture toughness specimens. The chemical composition of the plate is provided in Table 1.

Table 1. Chemical Composition of HSST Plate 13B (wt%).

C	Mn	P	S	Si	Ni	Cr	Mo	Cu
0.22	1.36	0.009	0.014	0.22	0.61	0.12	0.58	0.12

The room temperature yield and ultimate strengths are 444 and 600 MPa (64.4 and 87.0 ksi), respectively. The CVN 41-J transition temperature is -31°C (-87°F) while the upper-shelf energy is 139J (102 ft-lb). This plate has been selected for this study based on the large transition fracture toughness database that was previously generated on this plate by the Heavy Section Steel Irradiation HSSI) Program at ORNL. In that project, a large number of various specimen geometries and sizes, including 1T SE(B) and 1TC(T), have been used to develop fracture toughness transition fracture toughness temperatures, T_o. Details and complete results of this HSSI project have been previously published [2-3]. Table 2 provides a summary of T_o values that were generated with various specimen types and sizes within HSSI Program. In this Table, "N" is the total number of tested specimens while "r" is the number of ASTM E1921 valid specimens. The T_o values range from -69°C to -106°C.

Table 2. Summary of T_o values for HSST Plate 13B previously generated by large specimens.

Specimen Type	Number of tested specimens		T_o, °C
	N	r	
1T C(T)	29	29	-69
1T SE_{Bx2B}	17	17	-81
1T SE_{BxB}	20	18	-89
0.4T C(T)	23	23	-95
0.4T SE_{Bx2B}	20	17	-100
0.4T PCVN	65	41	-106

In addition to tests at ORNL, two sets of PCVN specimens were tested at Westinghouse and VTT. Both sets showed T_o values very similar to the one derived by ORNL (see Table 2). For consistency purposes, only ORNL generated data will be considered in this report.

Mini-CT specimens were machined from br ken halves of previously tested PCVN specimens. Four Mini-CT specimens were machined from one broken half of a PCVN (see Figure 1). The dimensions of the Mini-CT specimen are given in Figure 2. The design of the Mini-CT specimen for this study has been modified slightly compared to the design used in the CREPI round robin, [1]. The current design simplifies the machining and provides provision for load-line displacement measurement.

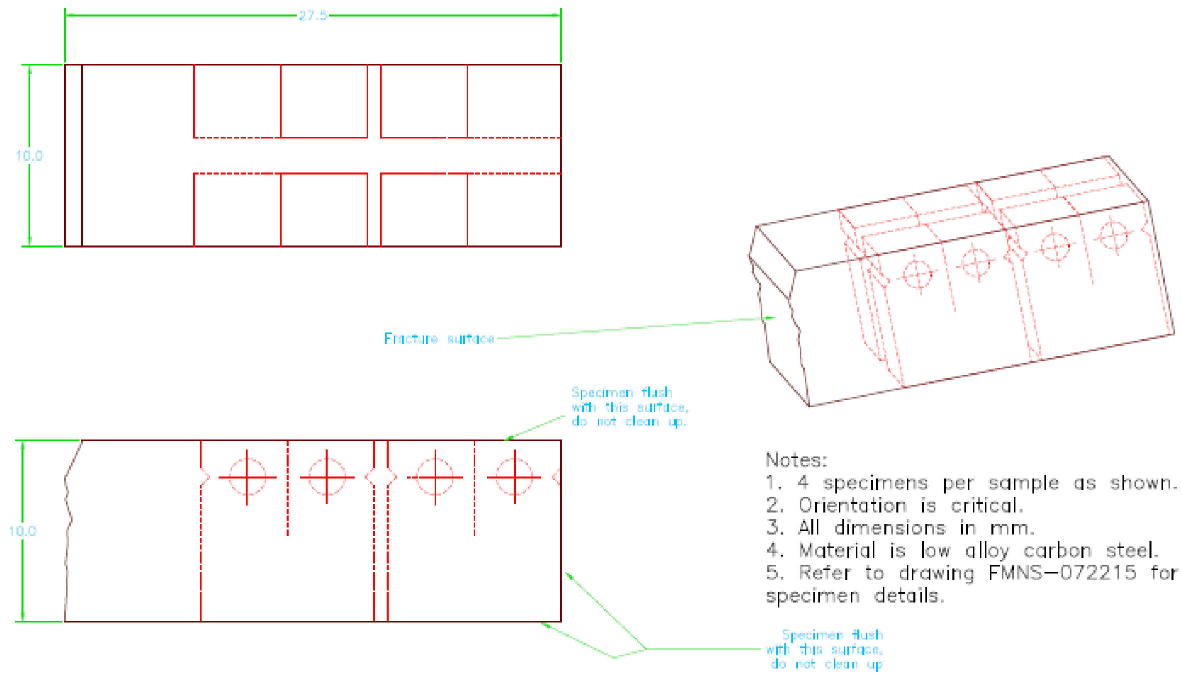

Figure 1. Layout of Mini-CT specimens from broken Charpy specimen.

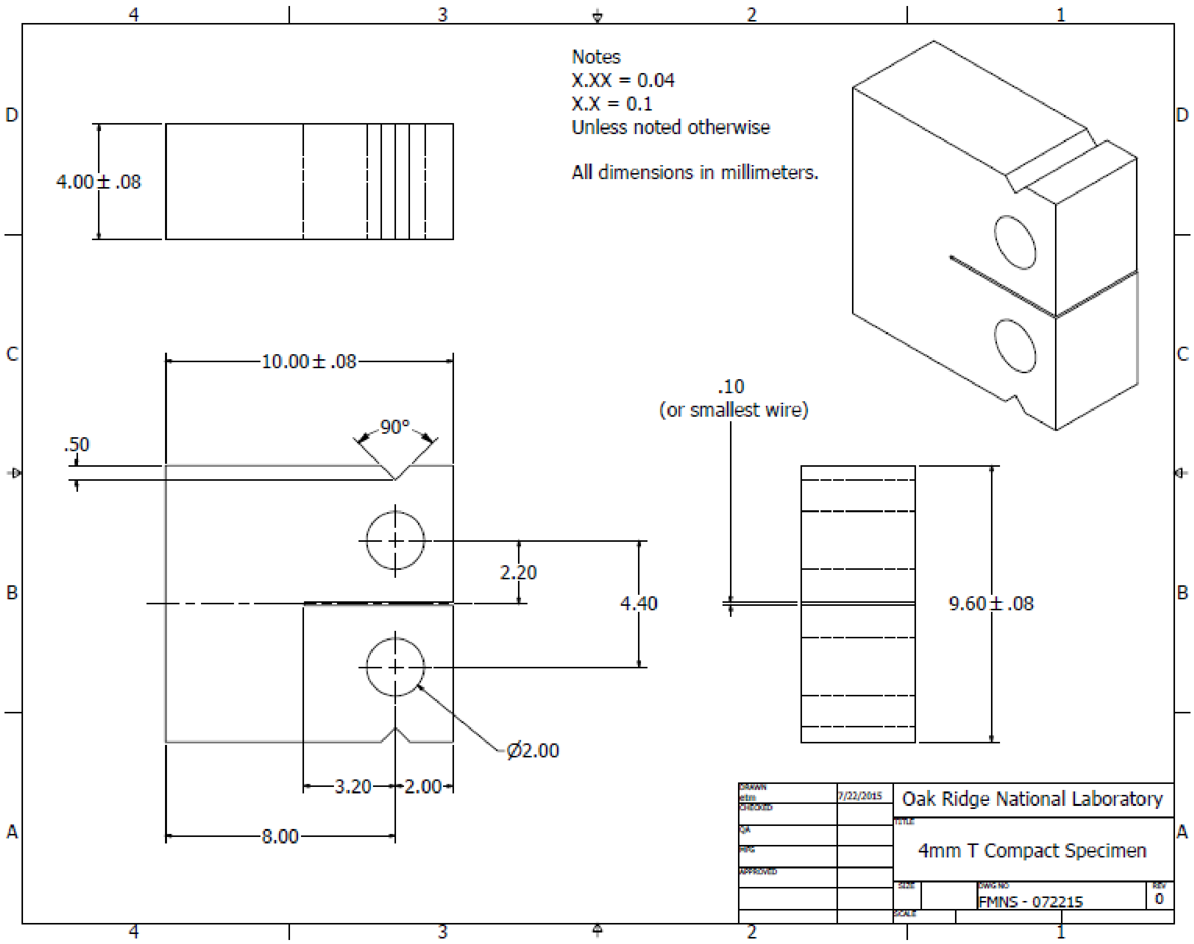

Figure 2. Mini-CT specimen used in this study.

A total of 15 Mini-CT specimens of HSST Plate 13B were tested in this program. Table 3 provides a summary of test results. Out of 15 total specimens, one specimen was determined to be invalid based on ASTM E1921 criteria and was censored during T_o calculation. The final value of the fracture toughness transition temperature, T_o, determined by Mini-CT specimens is -93°C. It is within the range of T_o values generated by larger specimens as reported in Table 2.

Figure 3 is a Weibull plot of the fracture toughness data determined by Mini-CT specimens in this study at -120°C. Thirteen specimens were tested at this temperature allowing for correspondence of the data scatter to be examined relative to the Weibull distribution function. The analysis showed that these data are well represented by Weibull statistics and the slope of fit to the data is equal to 3.9 which is an excellent match to the slope of 4 used in the Master Curve procedure of ASTM E1921 Standard.

Thus, the transition temperature determined by Mini-CT specimens is within the range of T_o values generated by larger specimens and fracture toughness data are following the Weibull distribution function as in the ASTM E1921 Standard.

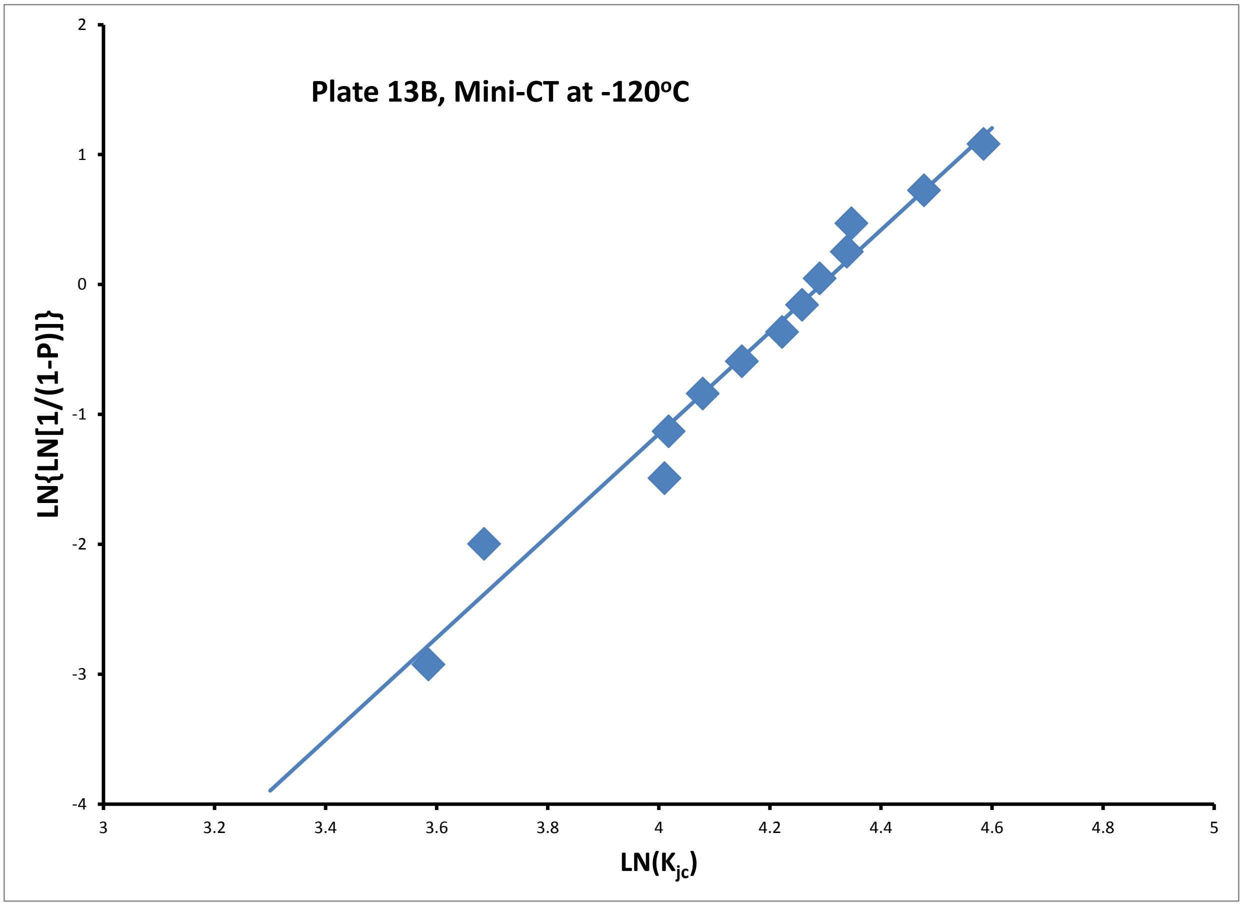

Figure 3. Weibull distribution plot of Mini-CT data at -120°C.

Table 3. Fracture toughness data of HSST Plate 13B measured by Mini-CT specimens.

Specimen ID	Temperature, °C	Measured K_{Jc}, MPa√m	Remarks
B-17-1	-140	119.7	
B-17-2	-140	61.6	
B-17-3	-120	110.9	
B-17-4	-120	82.1	
B-17-5	-120	100.4	
B-17-6	-120	76.5	
B-17-7	-120	143.8	invalid
B-17-8	-120	96.5	
E-39-1	-120	51.5	
E-39-3	-120	104.1	
E-39-4	-120	109.9	
E-39-5	-120	88.9	
E-39-6	-120	45.5	
E-39-7	-120	75.8	
E-39-8	-120	128.0	

3. BRIEF DISCRIPTION OF ONGOING ACTIVITIES ON ASSESSMENT AND VALIDATION OF MINI-CT SPECIMEN GEOMETRY

The next step in this project is validation of this specimen geometry for unirradiated weld metal that was previously well characterized with larger specimens. It was decided to select Midland beltline weld for this step since it was well characterized as part of 10^{th} HSSI Irradiation Series [4-5]. Mini-CT specimens have already been machined from this weld and will be characterized in FY2017.

The final step in assessment and validation of this specimen geometry for reactor pressure vessel steels will be performed using previously irradiated and characterized material. This will be performed as part of collaborative efforts between ORNL, CRIEPI and EPRI. It was decided to use the Midland beltline weld WF-70 that has been previously irradiated in Ford Reactor and characterized at ORNL [6]. As part of this collaboration, ORNL will provide broken halves of Charpy specimens. CRIEPI and EPRI will sponsor machining of Mini-CT specimens from the irradiated and previously tested Midland beltline weld specimens. Irradiated Mini-CT specimens will be sent to ORNL, CRIEPI, and an EPRI-designated laboratory to perform characterization of this material. After completion of all testing and analysis, a joint ORNL-CRIEPI-EPRI report will be published based on results of this international multi-laboratories effort.

4. SUMMARY

Assessment and validation of the Mini-CT specimen geometry has been performed on the previously well characterized HSST Plate 13B, an A533B class 1 steel. It was shown that the fracture toughness transition temperature measured by these Mini-CT specimens is within the range of T_o values that were derived from various large fracture toughness specimens. Moreover, the scatter of the fracture toughness values measured by Mini-CT specimens follows the Weibull distribution function providing additional proof for validation of this geometry for the Master Curve evaluation of rector pressure vessel steels.

An international collaborative program has been established to extend the assessment and validation efforts to unirradiated and irradiated weld metal. The program is underway and involves ORNL, CRIEPI, and EPRI.

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