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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6151
Managed and Operated by
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Fracture Toughness Reference Temperature T_o for HSSI Weld 72W

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FRACTURE TOUGHNESS REFERENCE TEMPERATURE T_O FOR HSSI WELD 72W*

R. K. Nanstad

ABSTRACT

The Heavy-Section Steel Irradiation Program at Oak Ridge National Laboratory (ORNL) conducted the Fifth Irradiation Series with two submerged-arc welds, HSSI Welds 72W and 73W. The weld wires for these welds were fabricated from a split-melt of steel with additional copper added to one half, such that the chemical compositions of the two weld wires are the same, except for the copper contents. About 15 m of weldment were fabricated for each weld and, for each weld in the unirradiated condition, a large number of compact type fracture toughness specimens, from 25.4 to 203.2 mm [1T to 8TC(T)], were tested at different temperatures. To accommodate the material needs for the Sixth Irradiation Series on crack-arrest toughness, additional welds were fabricated with the same weld wires and the same lot of welding flux as for the first batch. Because the same fabricator made the second batch of each weld from the same weld wire and the same lot of flux as the first batch, only Charpy V-notch impact specimens from the second batch were tested to verify the similarity of the two batches. Subsequently, the Materials Properties Council conducted a cooperative testing program with pre-cracked Charpy specimens of two RPV steels, one of which was HSSI Weld

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72W. The specimens of weld 72W were machined from the second batch. The results showed a disparity in the T_0 values of about 20°C between that determined from the pre-cracked Charpy specimens of the second batch and that from the fracture-toughness data using the first batch of 72W. These results raised the issue of similarity of the two batches of HSSI Weld 72W. To verify the similarity of the two batches, thirteen 1T compact specimens from the second batch of Weld 72W were machined and tested to provide a T_0 value comparable to that for the first batch. The T_o for this group of 1T specimens from the second batch is –53.4°C. This compares with a T_o for the first batch of –56.6°C. The overall T_o value for the combined database is –54°C. Thus, the test results indicate no significant difference in T_o values between the first and second batches. Therefore, the T_o result of –75°C from the MPC round robin program, with PCVN specimens, points to a difference of 21°C between the 1TC(T) and PCVN specimen for HSSI Weld 72W.

INTRODUCTION

The Heavy-Section Steel Irradiation Program at Oak Ridge National Laboratory conducted the Fifth Irradiation Series with two submerged-arc welds, HSSI Welds 72W and 73W[1-3]. The weld wires for these welds were fabricated from a split-melt of steel with additional copper added to one half such that the chemical compositions of the two weld wires are the same except for copper content, as shown in Table 1. The weld wire was produced by Combustion Engineering, Inc., CE-Wire, specifically for the HSSI Program. A total of 14.6 m of weld were fabricated in 1.22 m lengths by Combustion Engineering, Inc. for each weld and, for each weld in the unirradiated condition, a large number of compact type fracture toughness specimens from 25.4 to 203.2 mm [1T to 8TC(T)] were tested at different temperatures. Additionally, tensile, drop-weight, and a large number of Charpy impact specimens were also tested. Table 2 provides a summary of the mechanical properties for the two welds. To accommodate the material needs for the Sixth Irradiation Series on crack-arrest toughness [4,5], additional welds were fabricated with the same weld wires (0.156 in. diameter, A5.23-80, Electrode Classification EF-2 with additional chemical composition requirements, heat number 87984) and same lot of Linde 0124 welding flux (20×150 mesh, lot number 0103) as for the first batch. For base metal in the first batch, a 218 mm thick plate of A533 grade B class 2 steel was used, whereas a 234 mm thick plate of A533 grade B class 1 steel was used for the second batch. Because the same fabricator made the second batch of each weld from the same weld wire and same lot of flux as the first batch, only Charpy V-notch impact specimens from the second batch were tested to verify the similarity of the two batches. Subsequent to the completion of the Fifth and Sixth Irradiation Series, the Materials Properties Council conducted a cooperative testing program with pre-cracked Charpy V-notch (PCVN) specimens of two RPV steels, one of which was HSSI Weld 72W [6]. The specimens were machined from the second batch of weld 72W.

Nine laboratories from four countries participated in the MPC cooperative testing program. The program was conducted to evaluate the use of the PCVN specimen for the determination of T_o, the fracture toughness reference temperature according to ASTM Standard Test Method E 1921. The reference temperature T_o is the temperature at which the median value of K_{Jc} for a 1T specimen is 100 MPa√m according to E 1921. Each laboratory was supplied with 30 Charpy V-notch specimens to fatigue precrack and test in accordance with E 1921-97 and additional specifications delineated by the Cooperative Testing Program coordinator. As discussed in reference [6], three test temperatures were originally chosen for testing: -100, -85, and -65ºC. However, the initial results from three of the laboratories indicated that the fracture toughness results at -65ºC would be too high to provide valid K_{Jc} results, and the test temperatures were revised to -120, -100, and -75ºC. More than 250 PCVN specimens were tested, with 60 or more tests conducted at each test temperature.

Fig. 1 shows all the fracture toughness data for the first batch of unirradiated HSSI Weld 72W obtained in the Fifth Irradiation Series. The T_o value determined by ORNL prior to the establishment of the ASTM Standard was -54ºC [1–3]. Subsequent to the completion of the Fifth and Sixth Irradiation Series, the HSSI Program conducted testing with PCVN and 0.5TC(T) specimens of HSSI Weld 72W for various projects. The results of these tests are provided in Table 3 and Fig. 2 from reference [6]. For the results shown in Table 3, all specimens were side-grooved 20%. As shown, two groups of specimens were machined from the second batch of Weld 72W. For the five groups of PCVN specimens, the T_o values varied from -64 to -76ºC, with average T_o values of -76ºC for the first batch and -65ºC for the second batch.

Tabular results from the MPC Cooperative Testing Program are shown in Table 4[6], with the results shown graphically in Fig. 3, and a summary of the results in Table 5. The overall T_o value for the PCVN specimens is -75ºC. Thus, the results showed a disparity in the T_0 values of 21ºC between that determined from the PCVN specimens of the second batch and that from the compact specimen fracture toughness data using the “first batch” of 72W. These results raised the issue of similarity of the two batches of HSSI Weld 72W and precipitated the additional testing that is the subject of this report.

Table 1. Chemical compositions of HSSI Welds 72W and 73W

Material	Composition (wt %)[a,b]													
	C	Mn	P	S	Si	Cr	**Ni**	Mo	**Cu**	V	Co	Al	As	Sn
72W Mean	0.093	1.60	0.006	0.006	0.44	0.27	**0.60**	0.58	**0.23**	0.003	0.030	0.006	0.002	0.003
σ	0.006	0.038	0.0005	0.0005	0.024	0.008	**0.008**	0.008	**0.006**	0.0004				
73W Mean	0.098	1.56	0.005	0.005	0.45	0.25	**0.60**	0.58	**0.31**	0.003	0.030	0.006	0.002	0.003
σ	0.007	0.026	0.0004	0.0006	0.028	0.006	**0.006**	0.009	**0.010**	0.0001				
Base metal[c]	0.21	1.24	0.008	0.004	0.23	0.12	**0.66**	0.56	**0.11**	0.003	0.015	0.040	0.007	0.008

[a]For all materials, the following additional elements were determined: Cb < 0.01, Ta < 0.01, Ti < 0.01, B < 0.001, W < 0.01, and Zr < 0.001.
[b]Mean and standard deviations (σ) shown result from 84 and 77 separate analyses for 72W and 73W, respectively, taken from different locations throughout weldments.
[c]SA-533 grade B class 2 Lukens Melt No. B2511.

Table 2. Mechanical properties of HSSI Welds 72W and 73W in the unirradiated condition

Property	Weld 72W	Weld 73W
CVN 41-J transition temperature, ºC	-28	-39
CVN fracture appearance transition temperature, ºC	-1	-15
Drop-weight nil-ductility temperature, ºC	-23	-34
Reference temperature RTNDT, ºC	-23	-34
CVN upper-shelf energy, J	136	135
CVN upper-shelf lateral expansion, mm	2.119	2.082
0.2% offset yield strength at 24ºC, MPa	500.3	494.3
Ultimate tensile strength at 24ºC, MPa	609.0	603.6

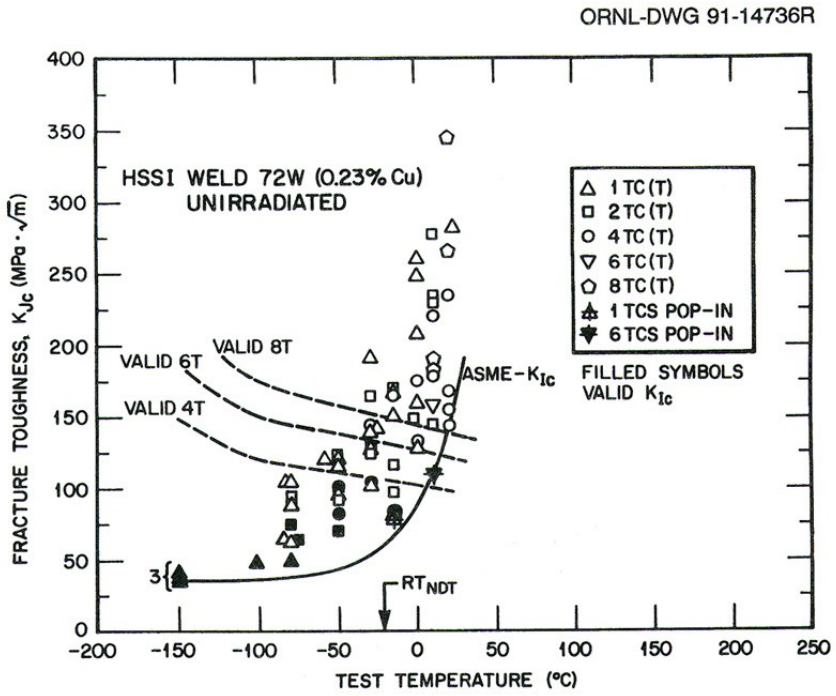

Fig. 1. Fracture toughness results for unirradiated HSSI Weld 72W from the HSSI Fifth Irradiation Series.

Table 3. Results of ORNL tests with PCVN and 0.5TC(T) specimens of HSSI Weld 72W

Material	Batch	Specimen Type	Test Temp (ºC)	No. of Specimens	$K_{Jc(med)}$ 1T (MPa√m)	Calculated T_o (ºC)
72W	1	0.5TC(T) 20% SG[a]	-64	8	96.2	-61.1
72W	1	0.5TC(T) 20% SG[a]	-86	8	62.3	-45.3
72W	1	PCVN 20% SG[a]	-86	10	87.9	-76.0
72W	2	PCVN 20% SG[a]	-64	10	101.2	-64.9
72W	2	PCVN 20% SG[a]	-95	10	70.7	-66.5

[a]SG means side-grooved.

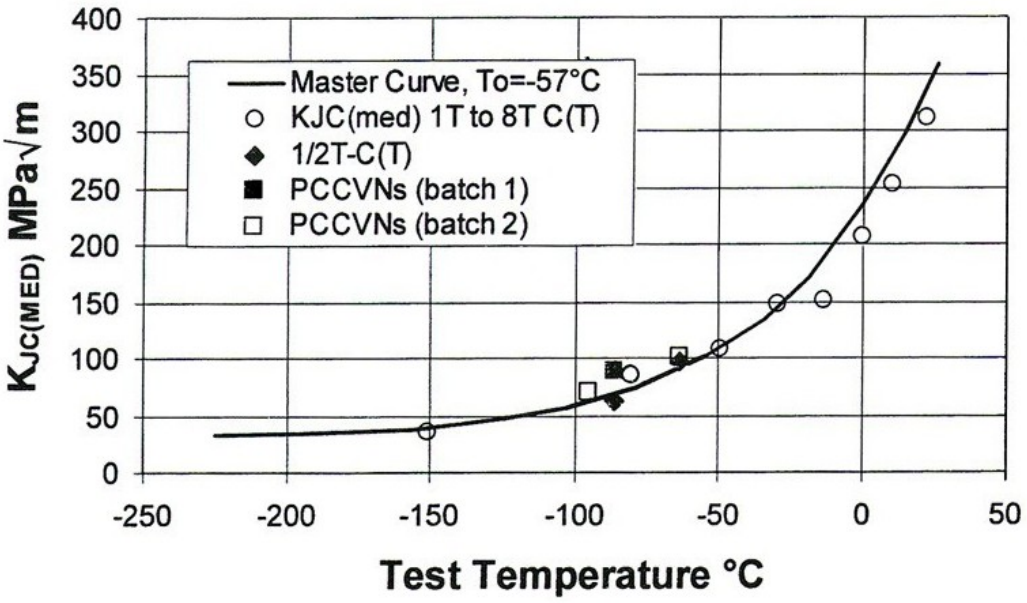

Fig. 2. Test results from ORNL tests with PCVN and 0.5TC(T) specimens of HSSI Weld 72W.

Table 4. Results of MPC Cooperative Test Program with PCVN specimens of HSSI Weld 72W, second batch

Laboratory		B	C	D	E	F	G	H	I	K
-65ºC	T_0, ºC							-73		
	$K_{Jc(med)}$, MPa√m							111.2		
	Number of valid Tests/number censored							12/5		
-75ºC	T_0, ºC	-71		-72	-57		-69	-84	-61	-64
	$K_{Jc(med)}$, MPa√m	95		95.6	79.4		91.1	112	83.1	91.6
	Number of valid Tests/number censored	10/3		11/2	6/0		8/2	10/5	7/0	9/1
-85ºC	T_0, ºC		-86			-75		-75		
	$K_{Jc(med)}$, MPa√m		98.5			87.5		88		
	Number of valid Tests/number censored		6/0			7/0		8/0		
-100ºC	T_0, ºC	-78	-89	-75	-76	-77	-84	-85	-53	-74
	$K_{Jc(med)}$, MPa√m	76.1	86.2	73.3	74.1	75	81.4	83	58.6	72.3
	Number of valid Tests/number censored	7/0	6/0	8/0	7/0	8/0	7/0	8/0	8/0	10/0
-120ºC	T_0, ºC	-68[1]	-84[1]	-90	-44[2]	-57[1]	-69	-99	-49[2]	-68
	$K_{Jc(med)}$, MPa√m	56.2	65.2	70	46.4	51.3	56.4	76.5	48.2	56.3
	Number of valid Tests/number censored	8/0	6/6	11	9/0	8/0	9/0	8/0	10/0	9/0

[1]Invalid because of number of test points
[2]Invalid because $K_{Jc(med)}$ below 50 MPa√m

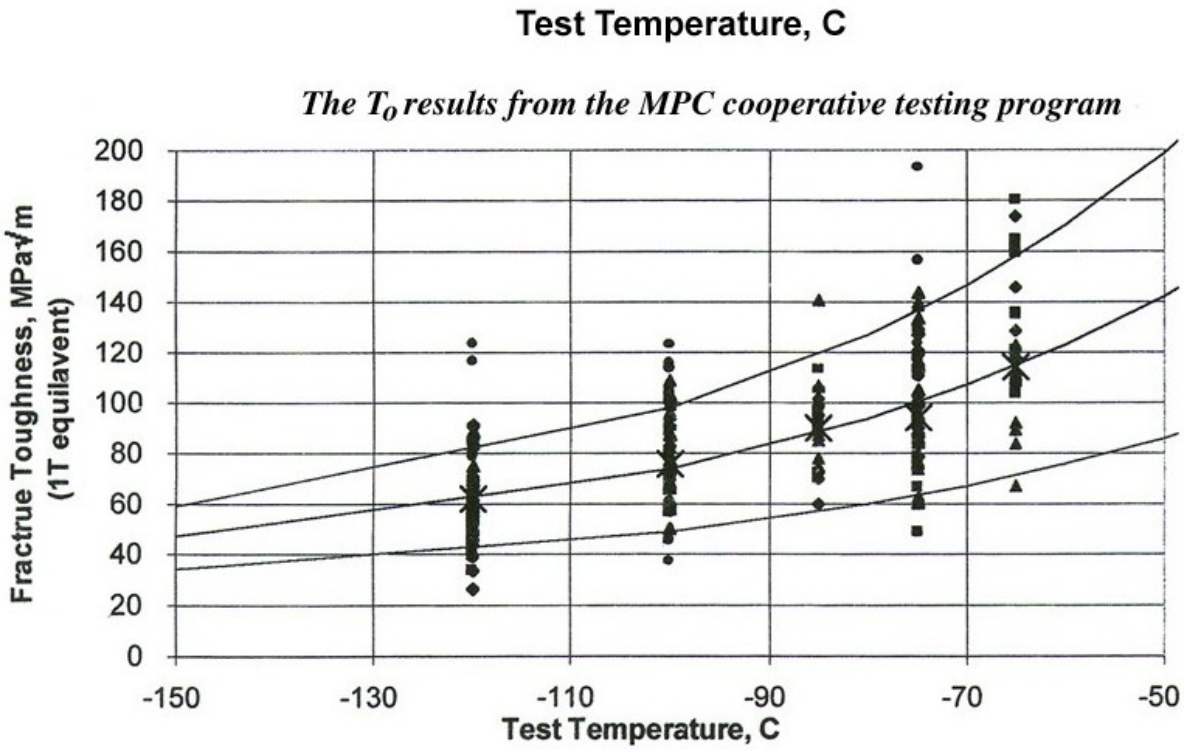

Fig. 3. Test results from MPC Cooperative Test Program with PCVN specimens of HSSI Weld 72W, Second Batch.

Table 5. Summary of Results from MPC Cooperative Test Program with PCVN specimens of HSSI Weld 72W, second batch

Test Temperature (ºC)	No. of valid tests	Range of $K_{Jc(med)}$ MPa√m	Range of T_o (ºC)	Overall T_o (ºC)[a]
-65	12	111.2	-73	-75
-75	61	79.4 to 112	-57 to -84	-70
-85	21	87.5 to 98.5	-75 to -86	-77
-100	69	58.6 to 86.2	-53 to -89	-78
-120[b]	37	56.3 to 76.5	-68 to -99	-79
All data combined	270[c]			-75

[a] T_o calculated according to ASTM E-1921-01 and using all data at the test temperature.
[b] A total of 78 valid tests were conducted at this temperature, but the resulting T_o values for individual data sets were declared invalid due to insufficient numbers of test values or $K_{Jc(med)}$ below 50 MPa√m; thus, this table reflects only the results from valid data sets.
[c] Includes the 41 valid tests not included in the result given at -120ºC.

TEST PLAN AND PROCEDURES

To verify the similarity of the two batches, thirteen 1T compact specimens were machined from the second batch of Weld 72W and tested to provide a T_0 value comparable to that obtained for the first batch. Specimens were machined in the T-L orientation, the same orientation as those from the first batch used for the Fifth Irradiation Series and the MPC Program. All the 1TC(T) specimens were fatigue pre-cracked in accordance with E 1921 to a/W ratios of about 0.52. As with the tests for the first batch, these specimens were not side-grooved and were cooled to the test temperatures with cold nitrogen gas. The specimen temperatures were monitored with a thermocouple spot-welded to the specimen. Tests were conducted at -30, -50, and -80ºC, three of the test temperatures used for the first batch. All tests were tested under computer control using an unloading compliance routine. The loading rate and test record analyses were performed in accordance with E 1921.

TEST RESULTS

The test results for the 1TC(T) specimens from the second batch of HSSI Weld 72W are presented graphically in Fig. 4 and tabulated in Table 6, which also includes the results from the first batch. As shown, the K_{Jc} results for the second batch range from 69 to 189 MPa$\sqrt{m}$. All results were substantially less than the $K_{Jc\text{-}limit}$ values and, as indicated on the figure, the T_o value is -53.4ºC.

The multi-temperature method of analysis in E 1921 was used to determine the reference temperature. Fig. 4 also shows the Master Curve for the second batch compared with that for the MPC PCVN data. As shown, the data are well represented by the Master Curve.

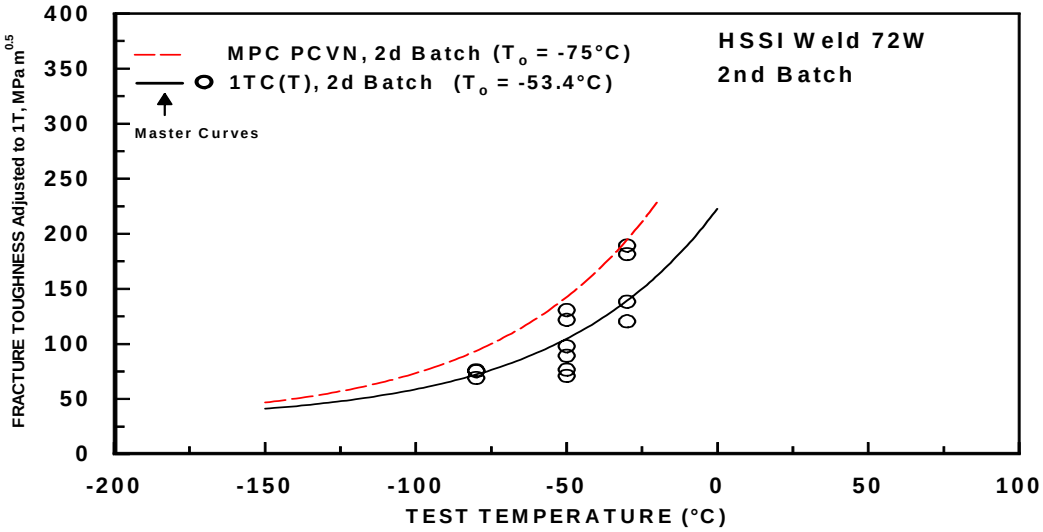

Fig. 4. Fracture toughness results from ORNL tests with 1TC(T) specimens of unirradiated HSSI Weld 72W, Second Batch, compared with the master curve for the MPC PCVN data.

Table 6. Results of ORNL tests with 1TC(T) specimens of HSSI Weld 72W, First and Second Batches

Specimen ID	Thickness (mm)	Width (mm)	Initial Crack Length (mm)	Initial Ligament (mm)	Test Temp (ºC)	Yield Strength (MPa)	Youngs's Modulus (MPa)	KJc-limit (MPa√m)	KJc (MPa√m)
Specimens from first batch									
72W135	25.4	50.8	26.52	24.28	-150	727.4	216	356	38.6
72W138	25.4	50.8	26.52	24.28	-150	727.4	216	356	39.0
72W113	25.4	50.8	26.87	23.93	-150	727.4	216	354	41.6
72W103	25.4	50.8	26.67	24.13	-101	618.9	213	326	46.8
72W168	25.4	50.8	27.64	23.16	-80	583.2	212	309	49.6
72W140	25.4	50.8	26.52	24.28	-80	583.2	212	316	62.7
72W164	25.4	50.8	27.84	22.96	-80	583.2	212	307	66.7
72W121	25.4	50.8	26.82	23.98	-80	583.2	212	314	92.6
72W127	25.4	50.8	27.03	23.77	-80	583.2	212	313	105.0
72W142	25.4	50.8	26.01	24.79	-80	583.2	212	319	106.0
72W105	25.4	50.8	26.82	23.98	-59	553.9	211	305	120.7
72W147	25.4	50.8	27.33	23.47	-50	543.3	210	299	96.1
72W156	25.4	50.8	27.43	23.37	-50	543.3	210	298	116.8
72W154	25.4	50.8	26.72	24.08	-50	543.3	210	303	118.7
72W157	25.4	50.8	26.92	23.88	-50	543.3	210	301	119.7
72W148	25.4	50.8	26.21	24.59	-50	543.3	210	306	121.8
72W153	25.4	50.8	30.07	20.73	-50	543.3	210	281	125.4
72W162	25.4	50.8	27.28	23.52	-30	524.0	209	293	102.6
72W158	25.4	50.8	26.82	23.98	-30	524.0	209	296	127.8
72W131	25.4	50.8	26.92	23.88	-30	524.0	209	295	139.7
72W133	25.4	50.8	27.23	23.57	-30	524.0	209	293	192.2
72W109	25.4	50.8	26.72	24.08	-26	520.8	209	295	142.2
72W161	25.4	50.8	26.92	23.88	-15	513.4	208	292	82.1
72W169	25.4	50.8	27.18	23.62	-15	513.4	208	290	86.3
72W170	25.4	50.8	27.13	23.67	-15	513.4	208	290	151.2
72W166	25.4	50.8	26.67	24.13	-15	513.4	208	293	168.7
72W165	25.4	50.8	25.96	24.84	0	506.0	207	295	128.7
72W151	25.4	50.8	26.67	24.13	0	506.0	207	290	160.3
72W128	25.4	50.8	26.87	23.93	0	506.0	207	289	208.5
72W160	25.4	50.8	26.01	24.79	0	506.0	207	294	249.0

Table 6. (Continued)

Specimen ID	Thickness (mm)	Width (mm)	Initial Crack Length (mm)	Initial Ligament (mm)	Test Temp (°C)	Yield Strength (MPa)	Youngs's Modulus (MPa)	KJc-limit (MPa√m)	KJc (MPa√m)
72W159	25.4	50.8	26.42	24.38	0	506.0	207	292	261.0
72W111	25.4	50.8	26.42	24.38	23	501.1	206	290	282.5
Specimens from second batch									
72WN5	25.4	50.75	26.72	24.03	-30	524.0	209	296	138
72WN7	25.4	50.68	26.58	24.10	-30	524.0	209	297	189
72WN11	25.4	50.66	26.36	24.29	-30	524.0	209	298	121
72WN12	25.4	50.66	26.09	24.57	-30	524.0	209	299	182
72WN1	25.4	50.75	26.48	24.27	-50	543.3	210	304	98
72WN3	25.4	50.67	26.80	23.87	-50	543.3	210	301	122
72WN4	25.4	50.67	26.18	24.50	-50	543.3	210	305	77
72WN6	25.4	50.71	27.36	23.34	-50	543.3	210	298	89
72WN9	25.4	50.70	26.18	24.52	-50	543.3	210	305	71
72WN10	25.4	50.65	26.75	23.89	-50	543.3	210	301	131
72WN2	25.4	50.87	26.48	24.40	-80	583.2	212	317	76
72WN8	25.4	50.68	26.49	24.19	-80	583.2	212	316	69
72WN13	25.4	50.68	27.00	23.67	-80	583.2	212	312	75

COMPARISON OF RESULTS WITH FIRST BATCH AND MPC PCVN DATA

Table 6 also provides the K_{Jc} data for the 32 1TC(T) specimens from the first batch, while Fig. 5 shows graphically the results.

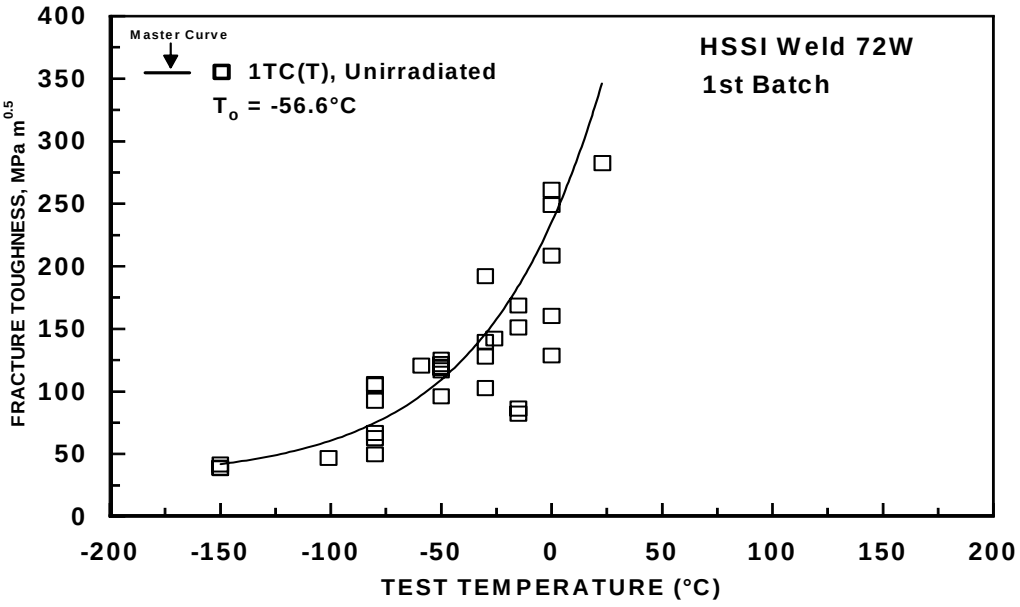

Fig. 5. Fracture toughness results from ORNL tests with 1TC(T) specimens of unirradiated HSSI Weld 72W, First Batch.

As shown in the figure, the T_o temperature for that group of specimens using the multi-temperature method is -56.6ºC. This compares with the value of -53.4ºC from the second batch, leaving a difference of only 3.2ºC. Fig. 6 provides a graphical comparison of the 1TC(T) data for both the first and second batches and shows the master curve for the combined group of 1TC(T) with that for the MPC PCVN data.

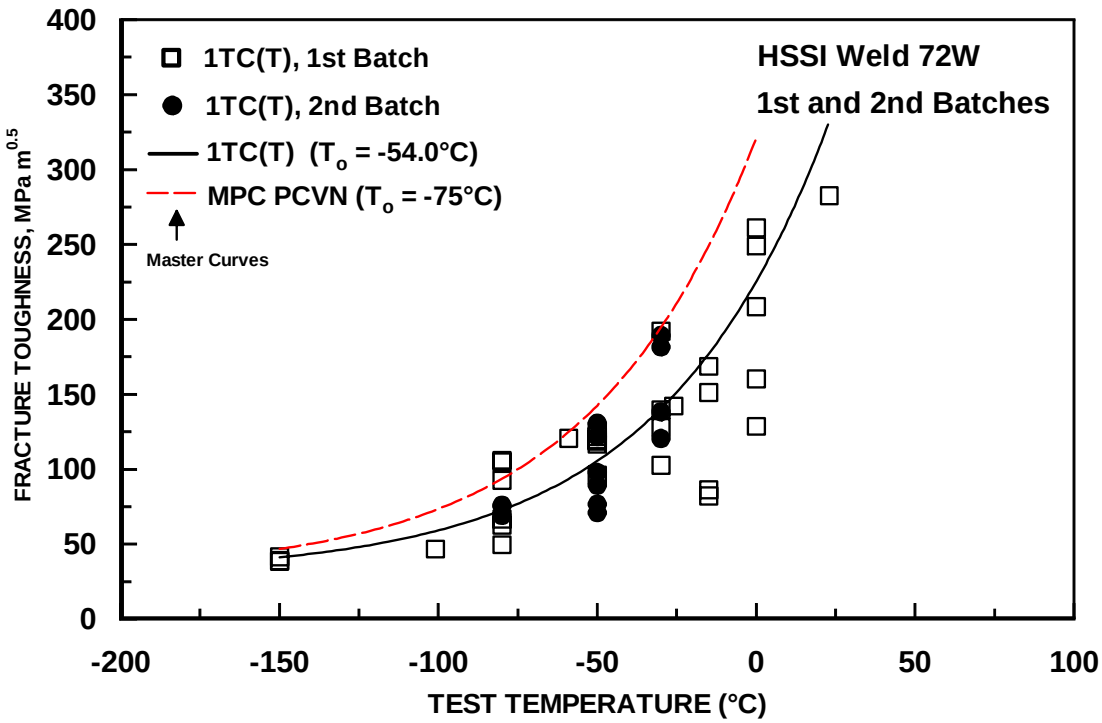

Fig. 6. Fracture toughness results from ORNL tests with 1TC(T) specimens of unirradiated HSSI Weld 72W, First and Second Batches. The master curves are shown for Weld 72W 1TC(T) (first and second batches) and the MPC PCVN.

The T_o temperature for the combined 1TC(T) data is -54.0ºC, the same value obtained from all the results in the Fifth Irradiation Series. Thus, the 1TC(T) data and the PCVN data from the MPC Cooperative Test Program, with T_o temperatures of -54º and -75ºC, respectively, exhibit a difference of 21ºC.

SUMMARY AND CONCLUSIONS

The Heavy-Section Steel Irradiation Program at Oak Ridge National Laboratory conducted the Fifth Irradiation Series with two submerged-arc welds, HSSI Welds 72W and 73W. Subsequent to that study, the MPC conducted a cooperative testing program with pre-cracked Charpy V-notch (PCVN) specimens of two RPV steels, one of which was HSSI Weld 72W. The specimens of 72W were machined from the second batch. The overall T_o value for the unirradiated compact specimens in the Fifth Irradiation Series was -54ºC, while that for the PCVN specimens in the MPC study was -75ºC, giving a 21°C disparity. These results implied a potential difference between the "first batch" and "second batch" of HSSI Weld 72W. To verify the similarity of the two batches, thirteen 1T compact specimens were machined from the second batch and tested. The 1TC(T) specimens from the second batch showed a T_o of -53.4ºC, compared with a T_o of -56.6ºC for the 1TC(T) specimens from the first batch. Thus, it is concluded that the fracture toughness reference temperatures are the same for the first and second batches, and the difference observed in the MPC study is attributed to the use of the three-point bend PCVN specimen.

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