Small-Scale Low-Constraint Fracture Toughness Test Results

Final Report 277-T-06

For Project

Weld Design, Testing, and Assessment Procedures for High Strength Pipelines

Prepared for the

Design, Materials, and Construction Technical Committee of
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Prepared by

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CANMET Materials Technology Laboratory

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FINAL REPORT STRUCTURE

Focus Area 1 - Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines		
Report #	**Description**	**Lead Authors**
277-T-01	Background of Linepipe Specifications	CRES/CANMET
277-T-02	Background of All-Weld Metal Tensile Test Protocol	CANMET/Lincoln
277-T-03	Development of Procedure for Low-Constraint Toughness Testing Using a Single-Specimen Technique	CANMET/CRES
277-T-04	Summary of Publications: Single-Edge Notched Tension SE(T) Tests	CANMET
277-T-05	Small Scale Tensile, Charpy V-Notch, and Fracture Toughness Tests	CANMET/NIST
277-T-06	Small Scale Low Constraint Fracture Toughness Test Results	CANMET/NIST
277-T-07	Small Scale Low Constraint Fracture Toughness Test Discussion and Analysis	CANMET/NIST
277-T-08	Summary of Mechanical Properties	CANMET
277-T-09	Curved Wide Plate Tests	NIST/CRES
277-T-10	Weld Strength Mismatch Requirements	CRES/CANMET
277-T-11	Curved Wide Plate Test Results and Transferability of Test Specimens	CRES/CANMET
277-S-01	Summary Report 277 Weld Design, Testing, and Assessment Procedures for High Strength Pipelines	CRES

Focus Area 2 - Development of Optimized Welding Solutions for X100 Linepipe Steel		
Report #	**Description**	**Lead Authors**
278-T-01	State of The Art Review	Lincoln
278-T-02	Material Selection, Welding and Weld Monitoring	Lincoln/CANMET
278-T-03	Microstructure and Hardness Characterization of Girth Welds	CANMET/Lincoln
278-T-04	Microstructure and Properties of Simulated Weld Metals	CANMET/Lincoln
278-T-05	Microstructure and Properties of Simulated Heat Affected Zones	CANMET/Lincoln
278-T-06	Essential Welding Variables	Lincoln/CANMET
278-T-07	Thermal Model for Welding Simulations	CRES/CANMET
278-T-08	Microstructure Model for Welding Simulations	CRES/CANMET
278-T-09	Application to Other Processes	Lincoln/CANMET
278-S-01	Summary Report 278 Development of Optimized Welding Solutions for X100 Line Pipe Steel	Lincoln

EXECUTIVE SUMMARY

This is the fifth report of a series of seven reports detailing the small-scale mechanical testing performed on the trial welds in this consolidated program. An outline of the reporting flow is given in the Introduction to the Summary of Mechanical Properties report 277-T-08. The present report contains the results of application of the low-constraint tensile toughness test, supplemented with results of shallow-notch bend tests, to the three series of welds in the consolidated program, including tests on base metal, weld metal, and HAZ.

Extensive single-edge notched tensile SE(T) and single-edge notched bend SE(B) tests of X100 linepipe girth-welds have been completed with the SE(T) procedure developed at CANMET and standard ASTM SE(B) procedures. The principal objective has been to provide data to correlate wide-plate performance from small-scale test results for development of a strain-based design procedure for the assessment of pipeline girth-weld integrity. This report includes experimental data for all SE(T) and SE(B) B×B specimens: J/CTOD-resistance curves, tables summarizing curve-fitting parameters for resistance curves, comparisons of measured crack lengths with unloading compliance crack length estimations, and fracture surface photographs. Additional SE(B) tests on B×2B specimens have been performed and are reported elsewhere.

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1 INTRODUCTION

This is the fifth report of a series of seven reports detailing the small-scale mechanical testing performed on the trial welds in this consolidated program. An outline of the reporting flow is given in the Introduction to the Summary of Mechanical Properties report 277-T-08. The present report contains the results of application of the low-constraint tensile toughness test, supplemented with results of shallow-notch bend tests, to the three series of welds in the consolidated program, including tests on base metal, weld metal, and HAZ.
The present report contains the results of application of the low-constraint tensile toughness test, supplemented with results of shallow-notch bend tests, and includes results of tests on the base metal, weld metal, and HAZ of the three rounds of welds in the consolidated program.

Single-edge notched tension [SE(T)] procedures and equations have been developed at CANMET [1] for J-integral calculation and J-resistance curve measurement with the use of the crack mouth opening displacement (CMOD) unloading compliance technique for a clamped SE(T) single specimen [2,3]. The crack tip opening displacement (CTOD) δ is also calculated from J and subsequently the CTOD-resistance curves are also generated from the CMOD unloading compliance technique. The intent is to generate small-scale data for comparison with wide plate crack growth performance to support strain-based design and evaluation of pipeline girth welds.

Extensive SE(T) and single-edge-notched bend [SE(B)] testing has been performed to provide the data for comparison with wide-plate test measurements being performed at the National Institute for Standards and Technology (NIST). This report contains the results from tests of X100 pipe steel base metal (BM) and the heat-affected zone (HAZ) and weld metal (WM) of pipeline girth welds. It includes summaries of experimental data for all SE(T) and SE(B) B×B small-scale specimens: J/CTOD-resistance curves, tables reporting power-law curve fitting parameters for resistance curves, comparisons of measured crack lengths with unloading compliance crack length estimations, and fracture surface photographs. Additional SE(B) tests on B×2B specimens have been done and are reported elsewhere [3].

2 OBJECTIVE

The objectives of the work reported here are to:

1. Develop procedures to apply the CANMET SE(T) procedure to pipeline girth welds (BM, HAZ and WM), and
2. Provide results of small-scale fracture toughness tests to be compared with those of wide plate tests for development of strain-based design.

3 MATERIAL, SPECIMEN PREPARATION AND TESTING

3.1 Material Properties and Specimen Preparation

(1) Pipe material: pipes of X100 (Grade 690), 914 mm (36 in) diameter by 19.1 mm (0.75 in) wall thickness (rounds 1 and 2) and 1067 mm (42 in) by 14.3 mm (0.563 in) wall thickness (round 3).

(2) Experimental pipeline welds: single torch (round 1) and dual torch (round 2) rolled girth welds (BM, HAZ and WM are shown in Figure 1); single torch 5G girth welds (round 3).

(3) Specimen length: 345 mm with an un-gripped length of $H = 10W = 172$ mm (rounds 1 and 2); ~240 mm with an un-gripped length of $H = 10W = 118$ mm (round 3).

(4) Specimen length direction: longitudinal to pipe axis (transverse to girth-weld).

(5) Cross-section: rounds 1 and 2, 17.5 mm × 17.5 mm for base metal and dual torch welds, weld metal centerline (WMC) and heat-affected zone (HAZ); and 17.2 mm × 17.2 mm for single torch welds; round 3, 11.8 mm × 11.8 mm for WMC and HAZ.

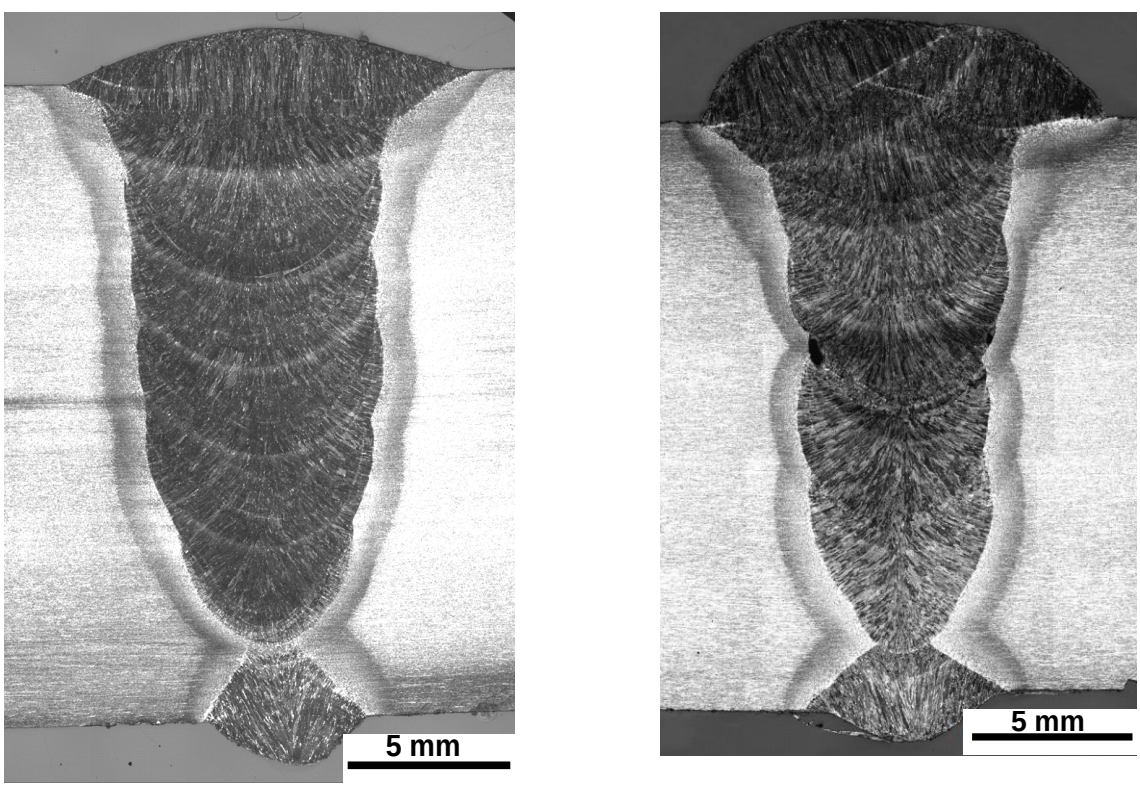
(6) Side-groove details: 45° included angle with 0.5 mm root radius to total depth of 15 % (7.5 % on each side) for rounds 1 and 2; total depth of 10 % (5 % on each side) for round 3.

(7) Targeted fatigue precrack depths: 3 mm and 6 mm (Figure 2).

(8) Notch and fatigue precrack: from inner diameter (ID) surface of the pipe.

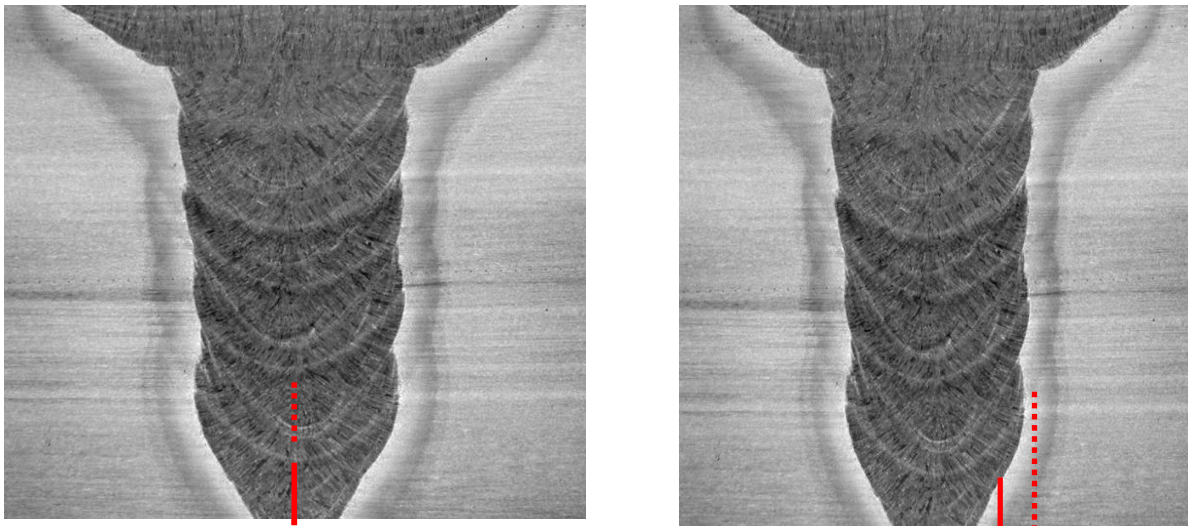
(9) Test temperatures: room temperature (RT), -20 °C and -40 °C (rounds 1 and 2); -20 °C (round 3).

(10) Local compression: No (rounds 1 and 2); Yes (round 3).



(a) **(b)**

Figure 1. X100 rolled welds: (a) single torch and (b) dual torch.



(a) **(b)**

Figure 2. Targeted precrack locations: (a) weld metal centerline and (b) HAZ, (solid line: 3 mm precrack and dotted line: 6 mm precrack).

3.2 SE(T) tests

Tables 1-4 summarize the SE(T) test matrices.

Table 1. SE(T) test matrix for X100 base metal

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)
RT	a = 3 mm a = 6 mm	2 (BMRTK06, K09) 4 [BMRTK12, K13, K14, K02(20 %SG)]
-20 °C	a = 3 mm a = 6 mm	1 (BMLTK10) 1 (BMLTK11)

Table 2. SE(T) test matrix for single torch X100 rolled welds (round 1)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
RT	a = 3 mm a = 6 mm	2 (WMRTK01, K22) 2 (WMRTK11, K19)	2 (HZRTK07, K21) 2 (HZRTK18, K20)
-20 °C	a = 3 mm a = 6 mm	4 (WMLTK02, K15, K23) 3 (WMLTK12, K13, K14)	3 (HZLTK08, K09, K16) 3 (HZLTK05, K06, K17)
-40 °C	a = 3 mm	2 (WMLT4K24, K25)	2 (HZLT4K26, K27)

Table 3. SE(T) test matrix for dual torch X100 rolled welds (round 2)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
RT	a = 3 mm a = 6 mm	2 (WMRTF02, F09) 2 (WMRTF04, F11)	2 (HZRTF05, F14) 2 (HZRTF07, F16)
-20 °C	a = 3 mm a = 6 mm	2 (WMLTF10, F102) 2 (WMLTF03, F12)	2 (HZLTF06, F13) 2 (HZLTF08, F28)

Table 4. SE(T) test matrix for single torch X100 5G welds (round 3)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
-20 °C	a = 3 mm	3 (DW1-B, DW3-A, DW6-A) 3 (FW1-A, FW3-A, FW6-A)	3 (DH1-A, DH3-A, DH6-A) 3 (FH1-A, FH3-A, FH6-A)

3.3 SE(B) tests

Tables 5-8 summarize SE(B) test matrices.

Table 5. SE(B) test matrix for base metal

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)
RT	a = 6 mm	2 (BBMRT1, T2)
-20 °C	a = 3 mm	5 (BM2, BM3, BM4, BM5, BM6)

Table 6. SE(B) test matrix for single torch X100 rolled welds (round 1)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
RT	a = 3 mm a = 6 mm	2 (BWMRTG05, I10) 2 (BWMRTI04, I11)	2 (BHZRTI05, I06) 2 (BHZRTG04, I08)
-20 °C	a = 3 mm a = 6 mm	2 (BWMLTI01, I02) 2 (BWMLTG06, I12)	2 (BHZLTI13, I14) 2 (BHZLTG08, I15)

Table 7. SE(B) test matrix for dual torch X100 rolled welds (round 2)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
RT	a = 3 mm a = 6 mm	1 (BWMRTF21) 1 (BWMRTF23)	1 (BHZLTF25) -
-20 °C	a = 3 mm a = 6 mm	1 (BWMLTF22) 1 (BWMLTF24)	1 (BHZLTF26) -

Table 8. SE(B) test matrix for single torch X100 5G welds (round 3)

Temperature, °C	Target Crack Length	Number of specimens (specimen ID)	
		WMC	HAZ
-20 °C	a = 3 mm	3 (DW1, DW3, DW6) 3 (FW1, FW3, FW6)	3 (DH1, DH3, DH6) 3 (FH1, FH3, FH6)

4 RESISTANCE CURVES

This section includes J/CTOD resistance curves for all SE(T) and SE(B) tests of BM, HAZ and WM. The targeted crack lengths, test temperatures and fracture toughness at the peak loads are indicated. In the figures, symbols indicate raw data calculated from experimental measurements, and solid lines represent power-law curve fits to raw data.

4.1 J-R Curves

4.1.1 SE(T)

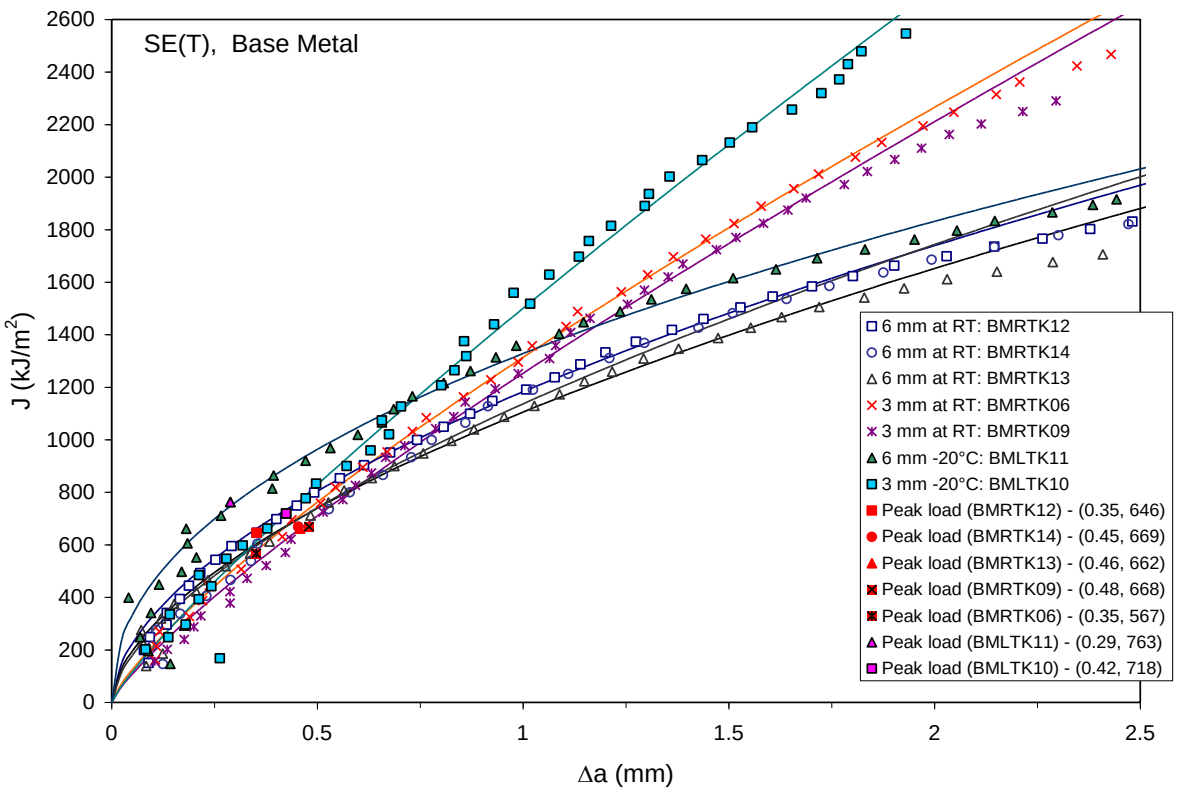
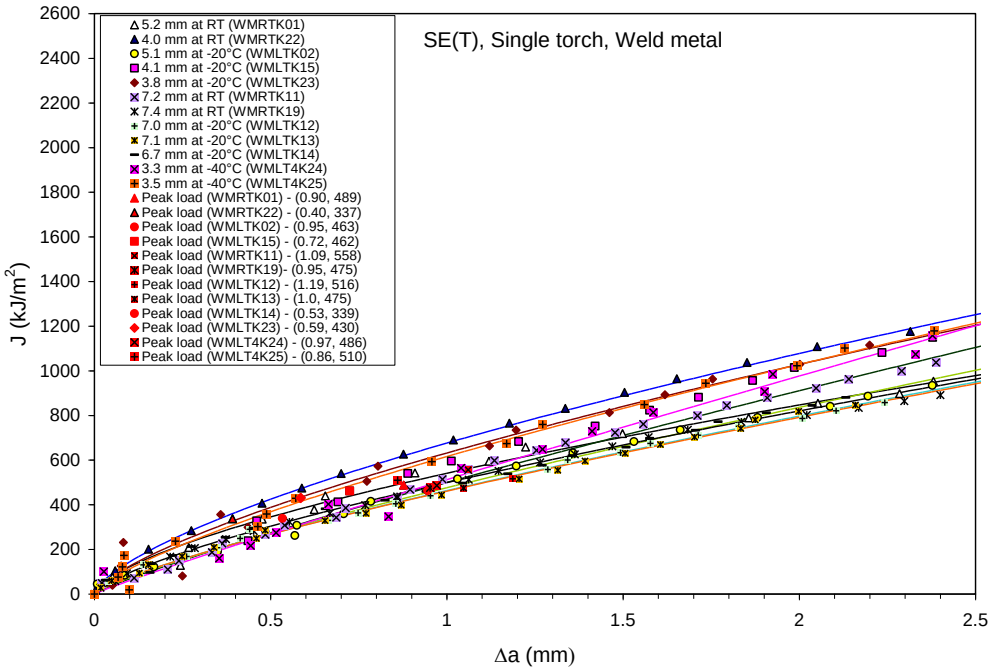
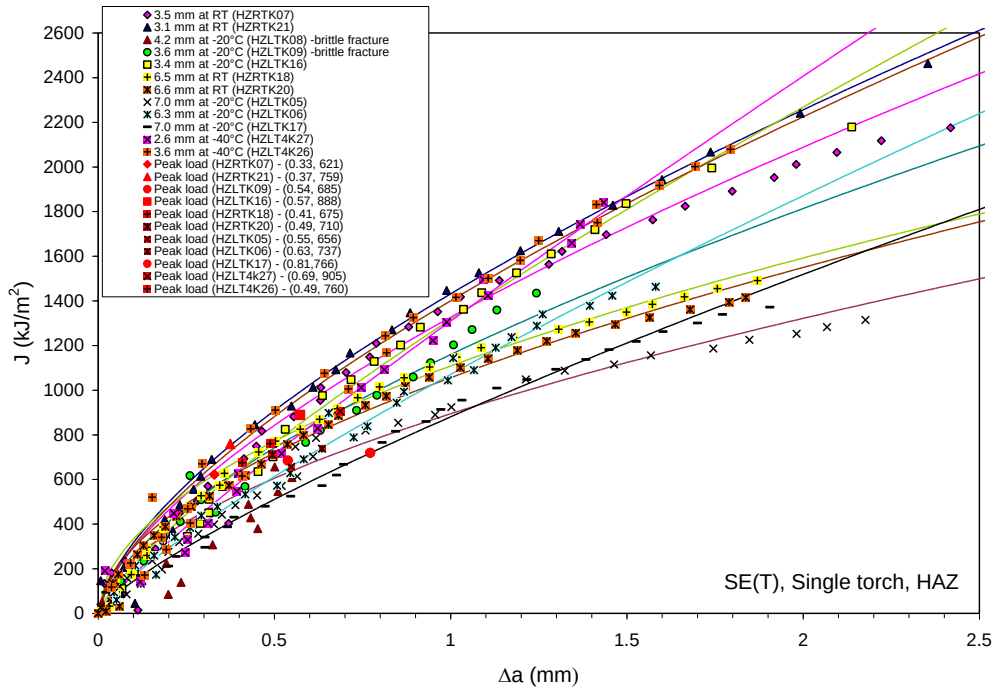


Figure 3. J-resistance curves for SE(T) tests of the X100 pipe steel base metal.

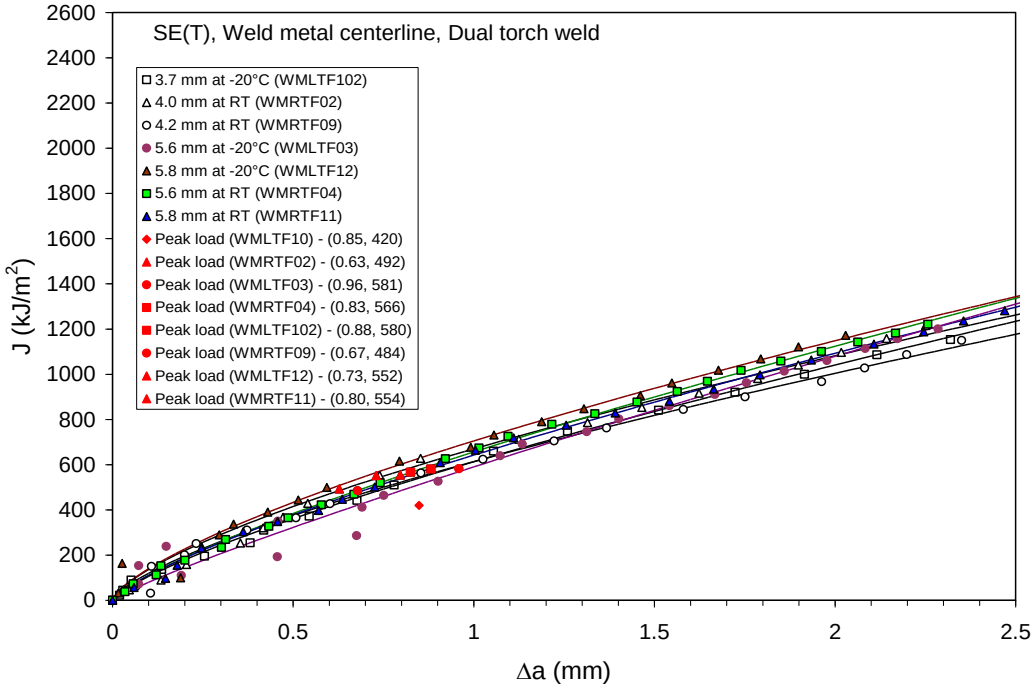


(a)

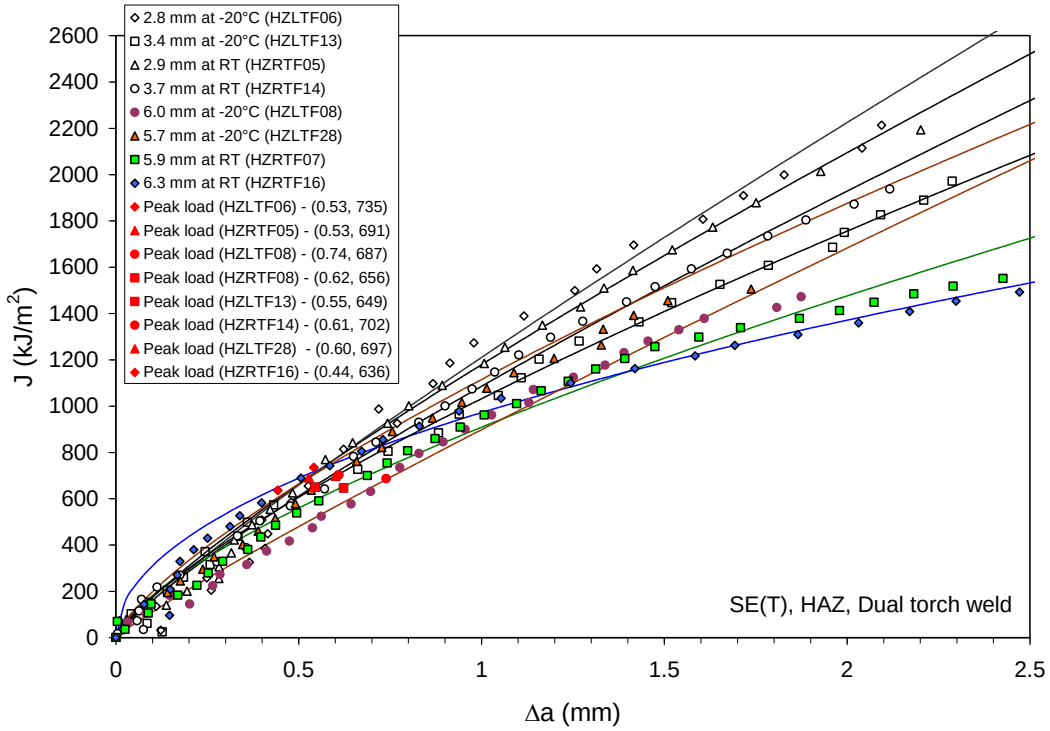


(b)

Figure 4. SE(T) J-resistance curves for single torch (round 1) (a) weld metal and (b) HAZ.

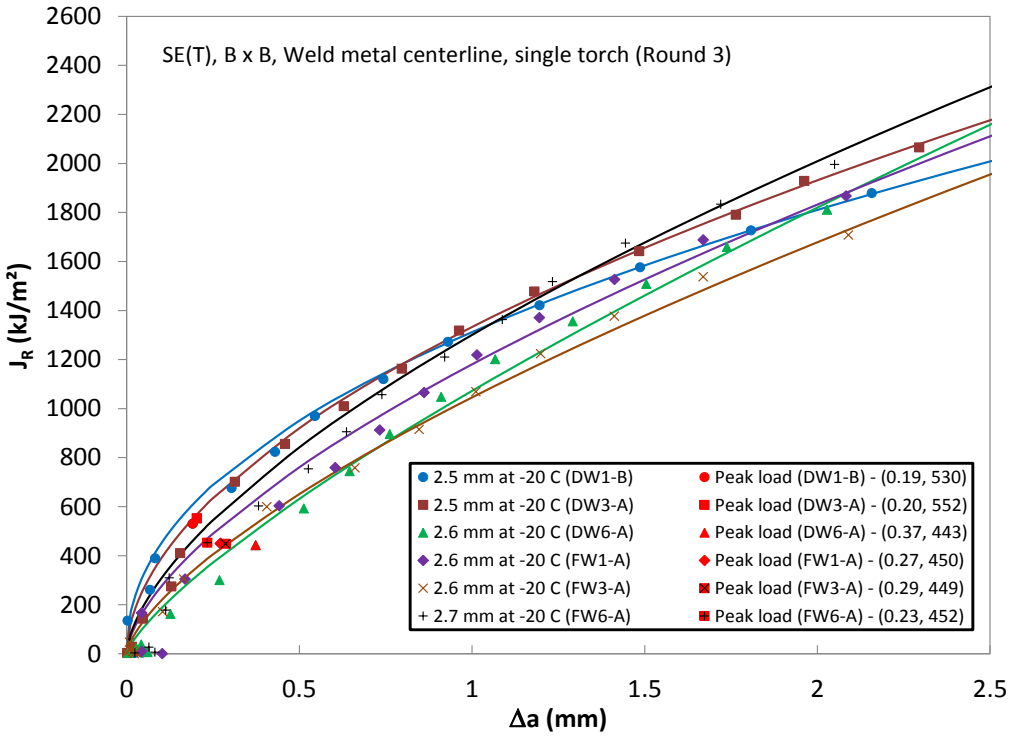


(a)

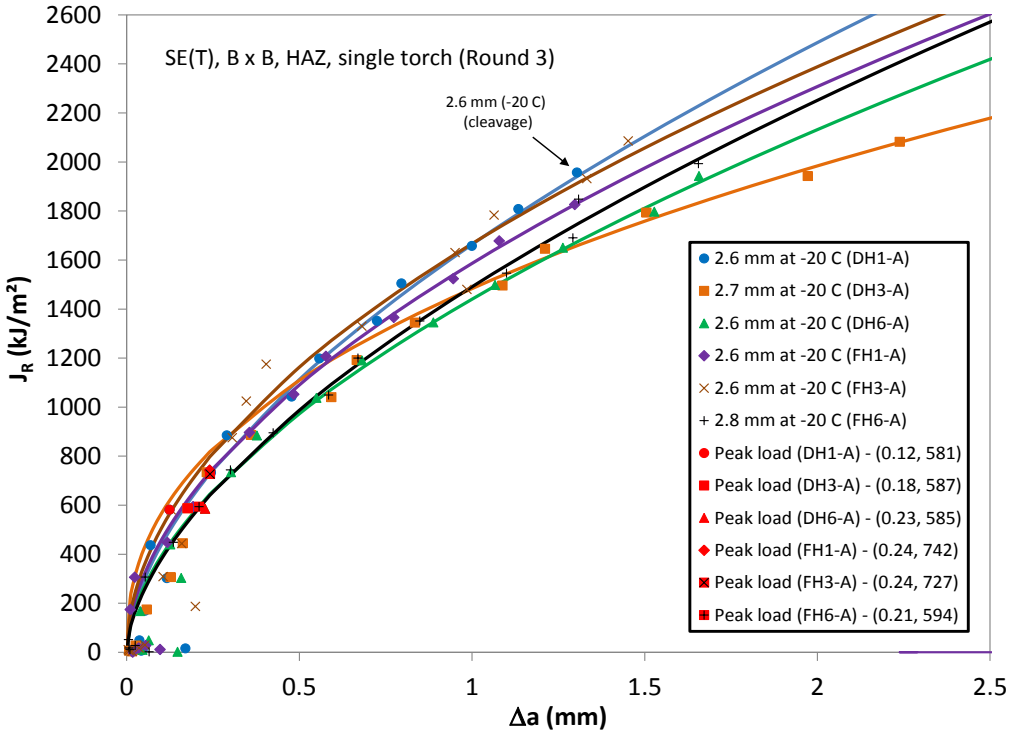


(b)

Figure 5. SE(T) J-resistance curves for dual torch (round 2) (a) weld metal and (b) HAZ.



(a)



(b)

Figure 6. SE(T) J-resistance curves for single torch (round 3) (a) weld metal and (b) HAZ.

4.1.2 SE(B)

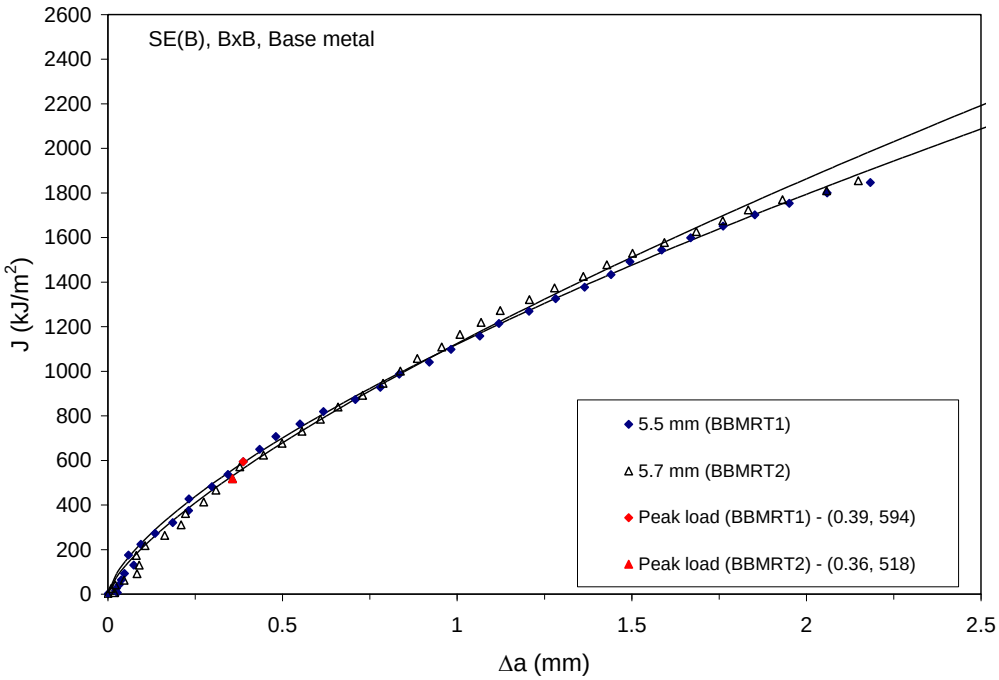


Figure 7. SE(B) J-resistance curves for the X100 pipe steel base metal at room temperature (rounds 1 and 2).

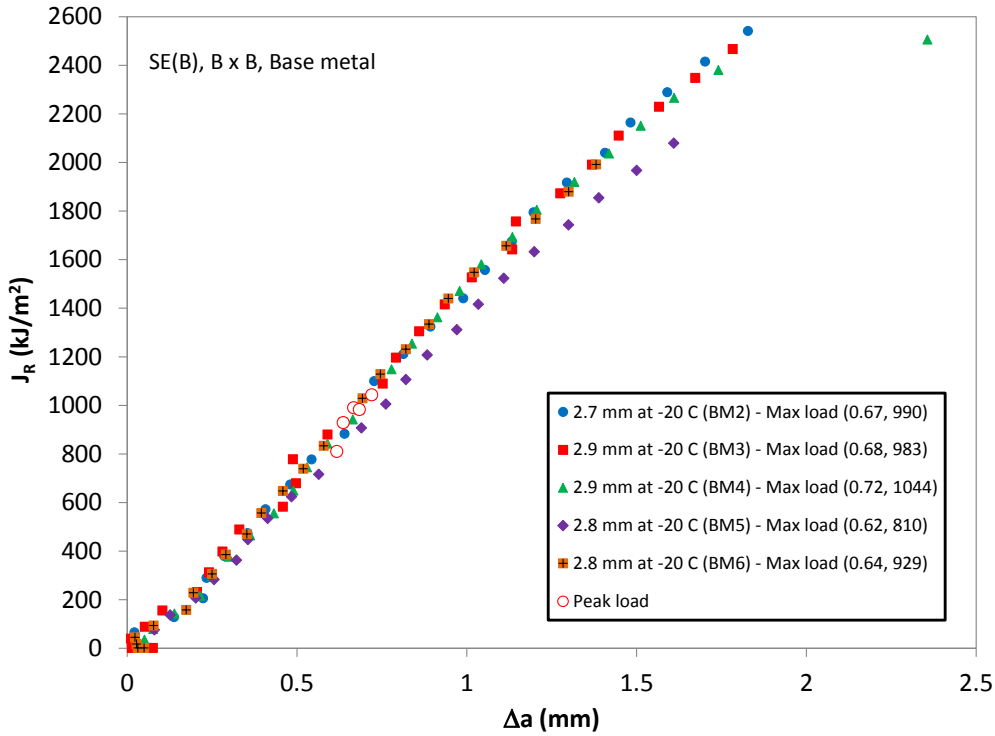
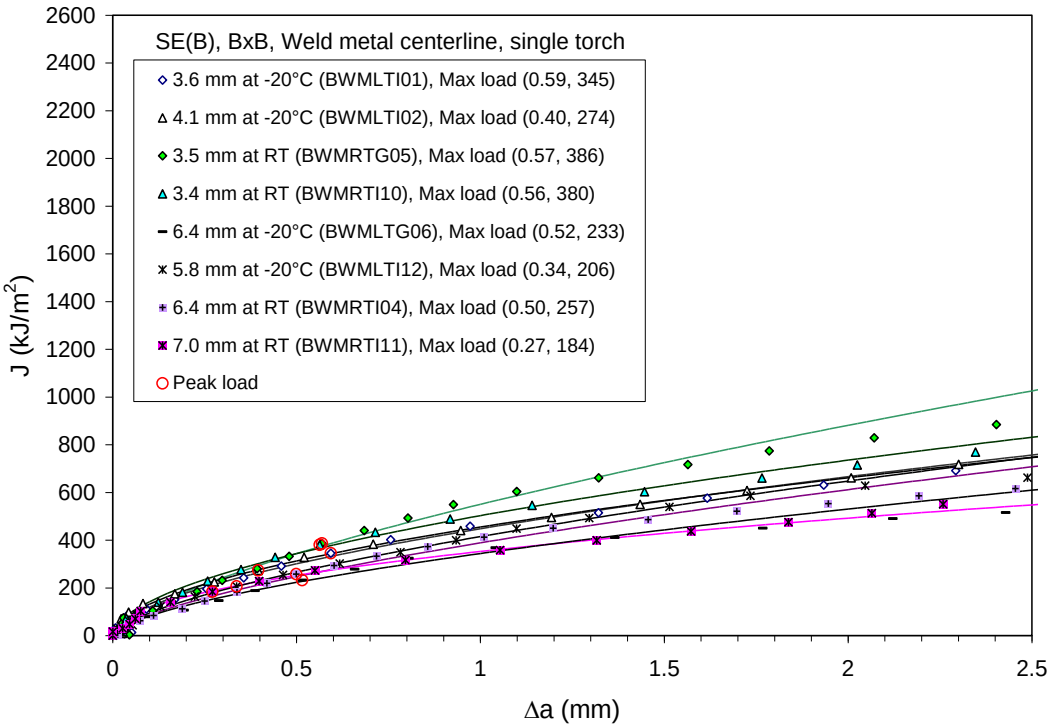
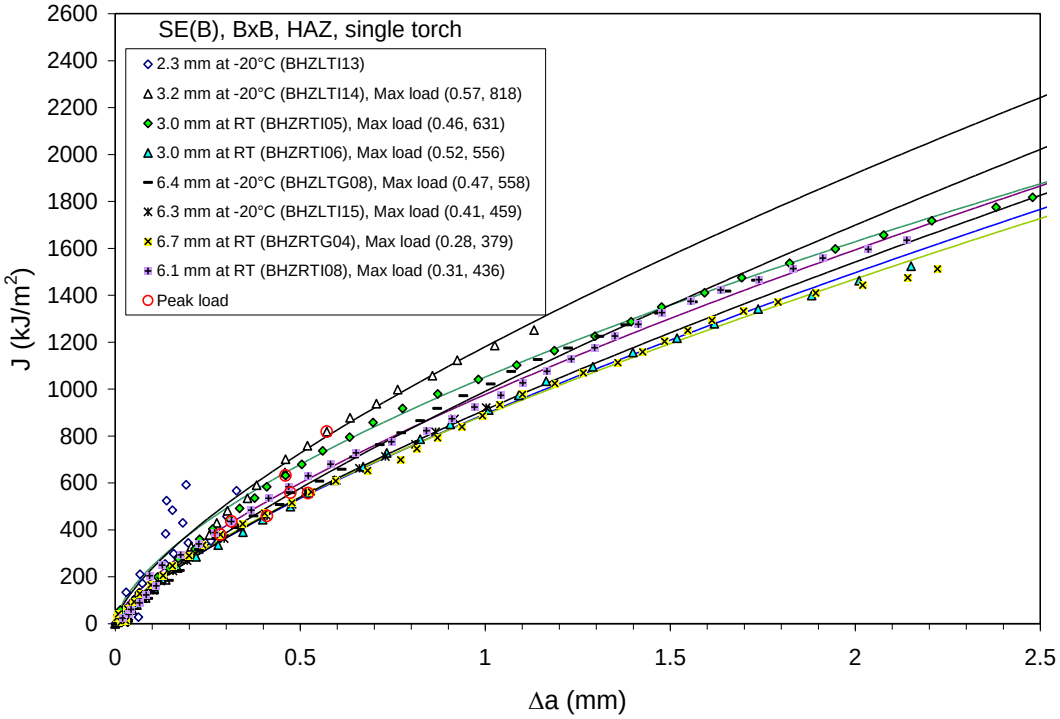


Figure 8. SE(B) J-resistance curves for the X100 pipe steel base metal (round 3).

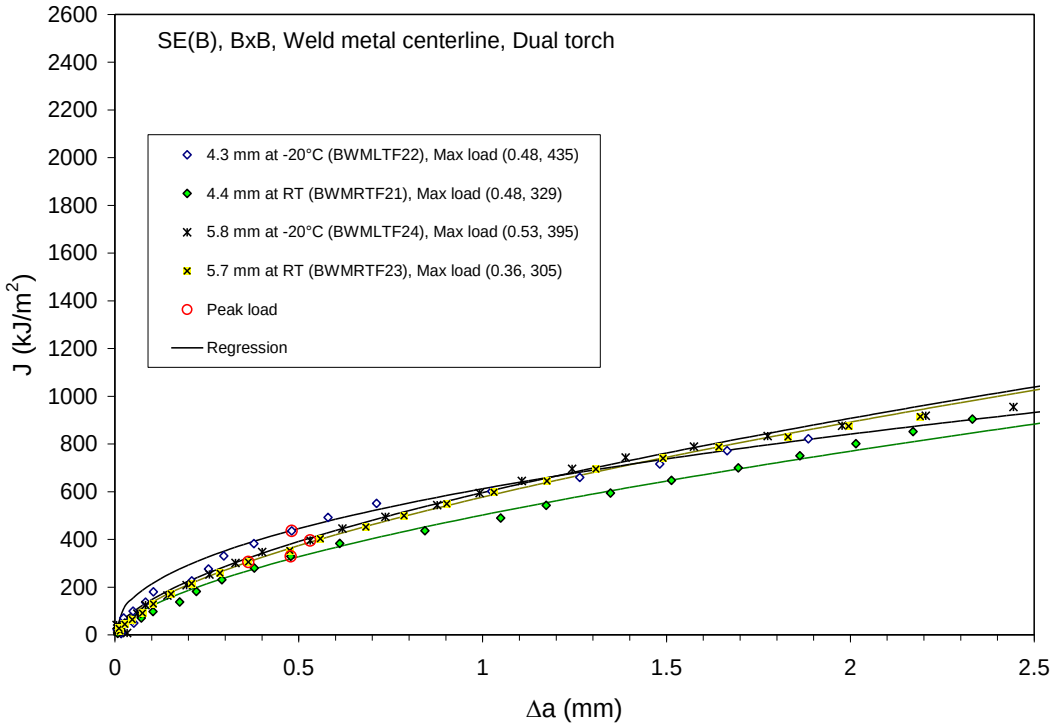


(a)

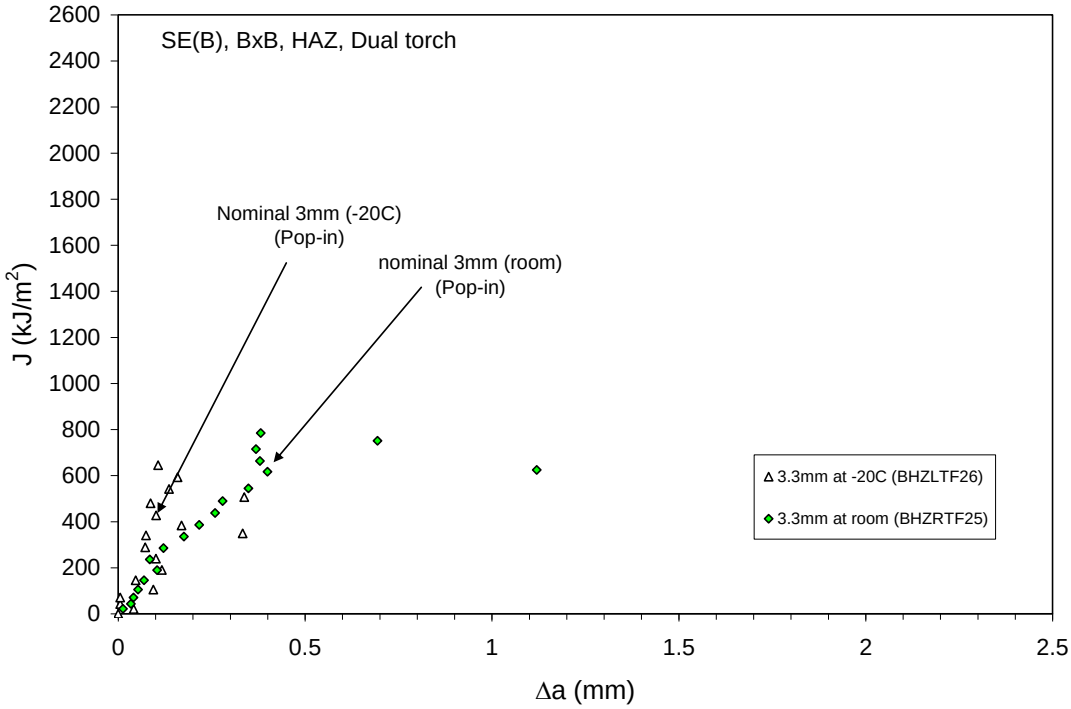


(b)

Figure 9. SE(B) J-resistance curves for single torch (round 1) (a) weld metal and (b) HAZ.

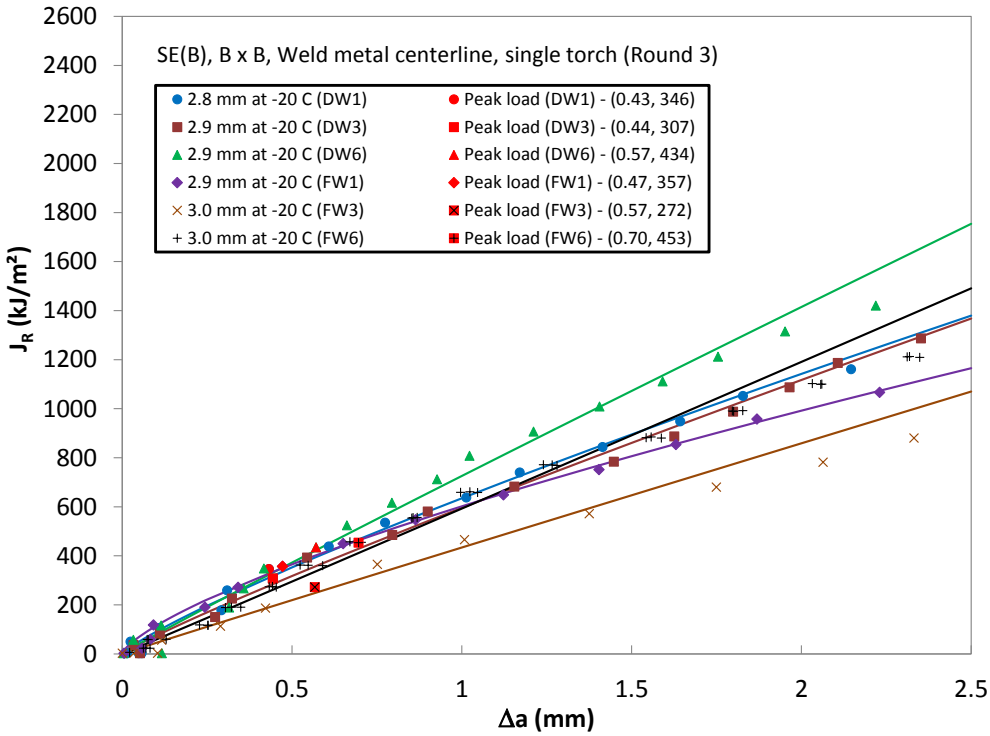


(a)

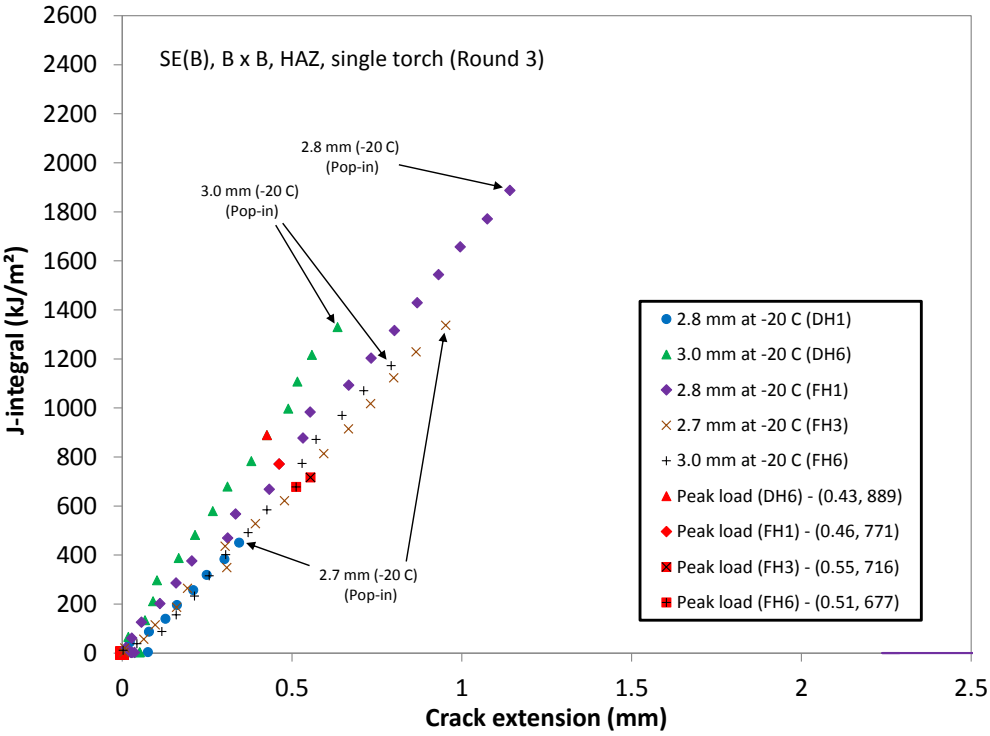


(b)

Figure 10. SE(B) J-resistance curves for dual torch (round 2) (a) weld metal and (b) HAZ.



(a)



(b)

Figure 11. SE(B) J-resistance curves for single torch (round 3) (a) weld metal and (b) HAZ.

4.2 CTOD-R Curves

4.2.1 SE(T)

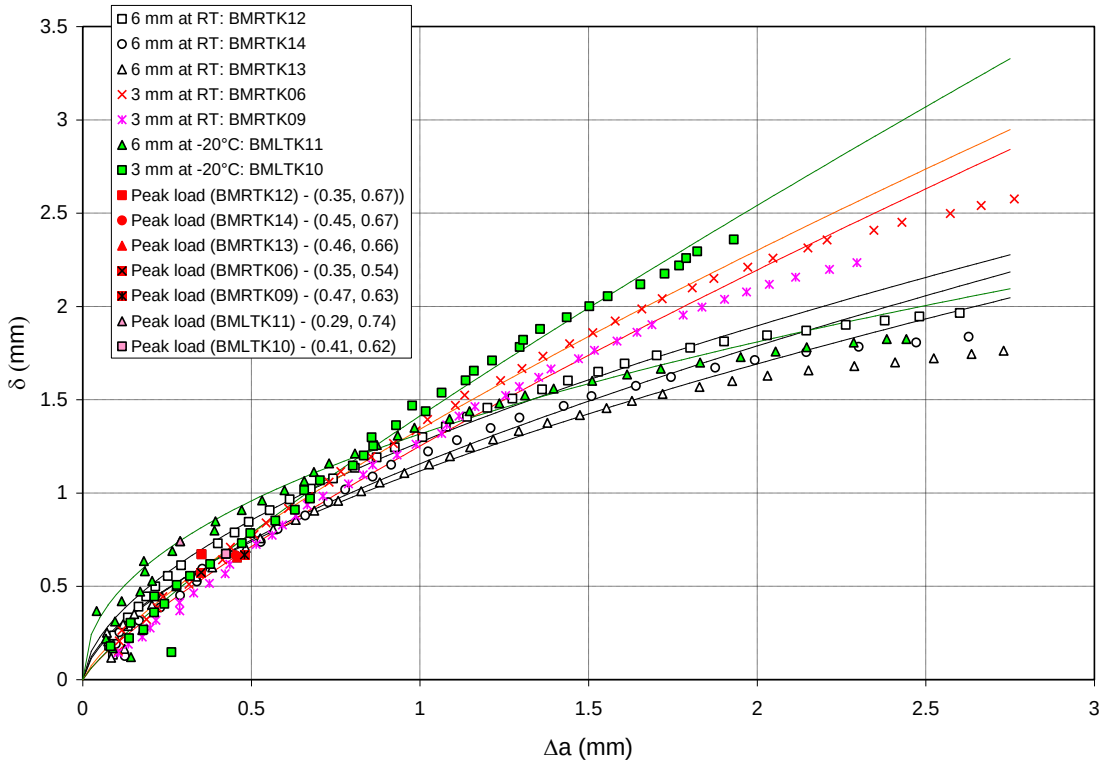
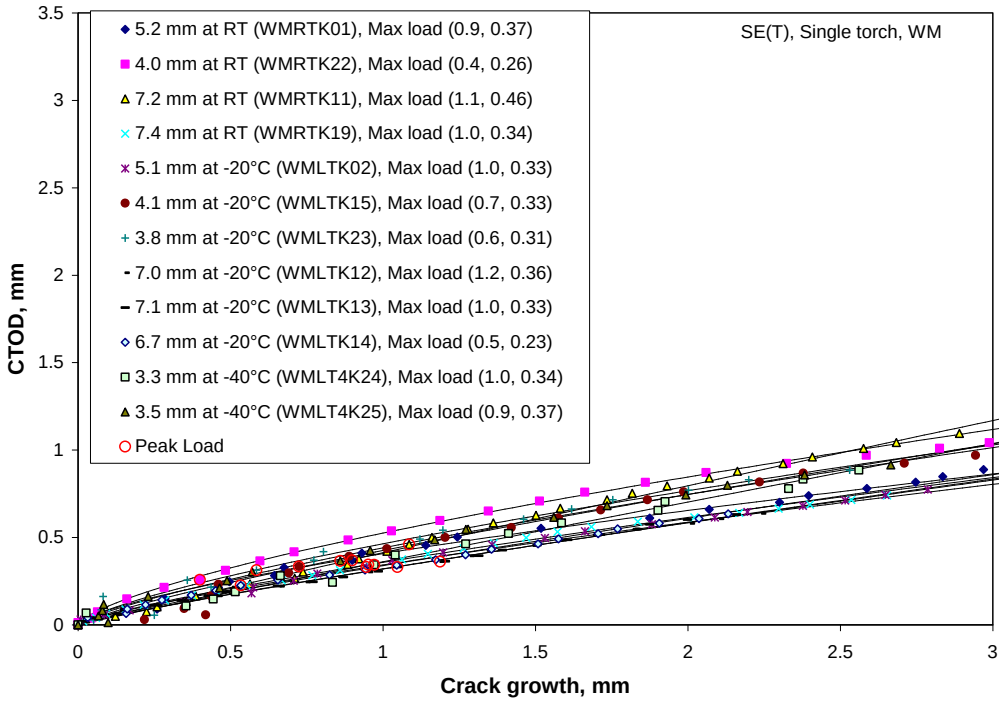
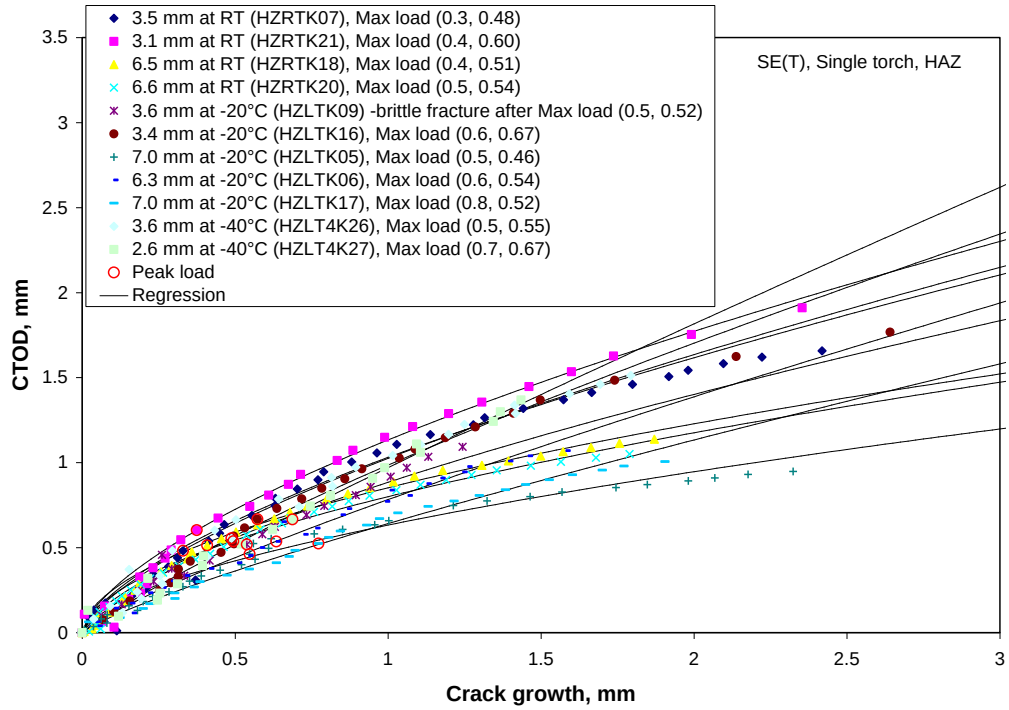


Figure 12. SE(T) CTOD-resistance curves for X100 pipe steel base metal.

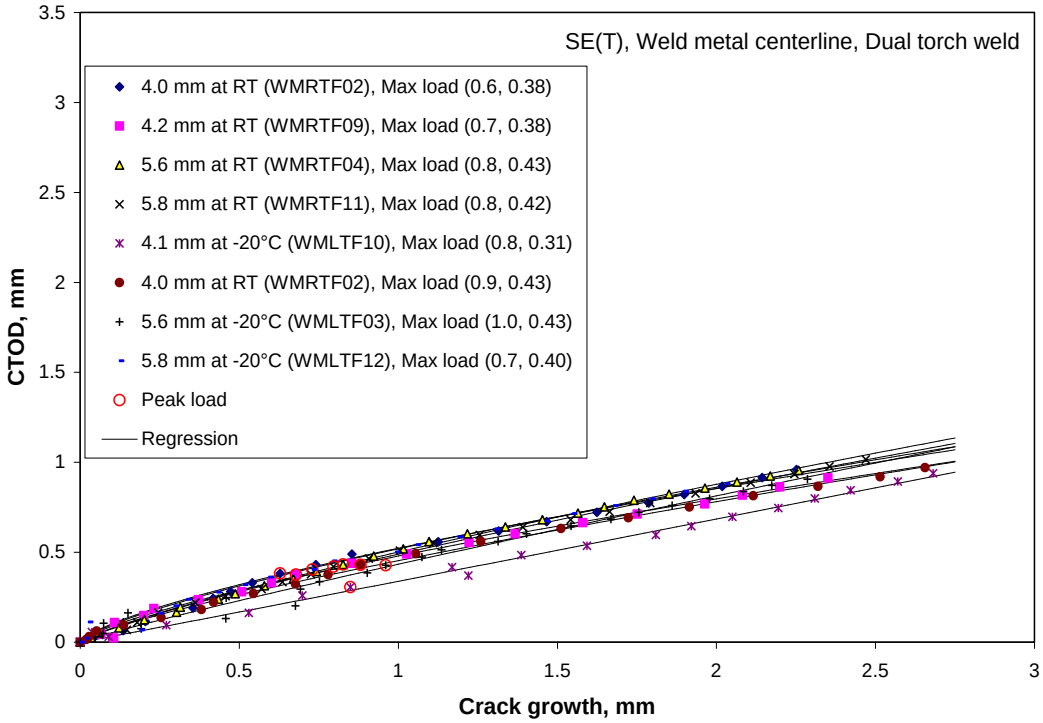


(a)

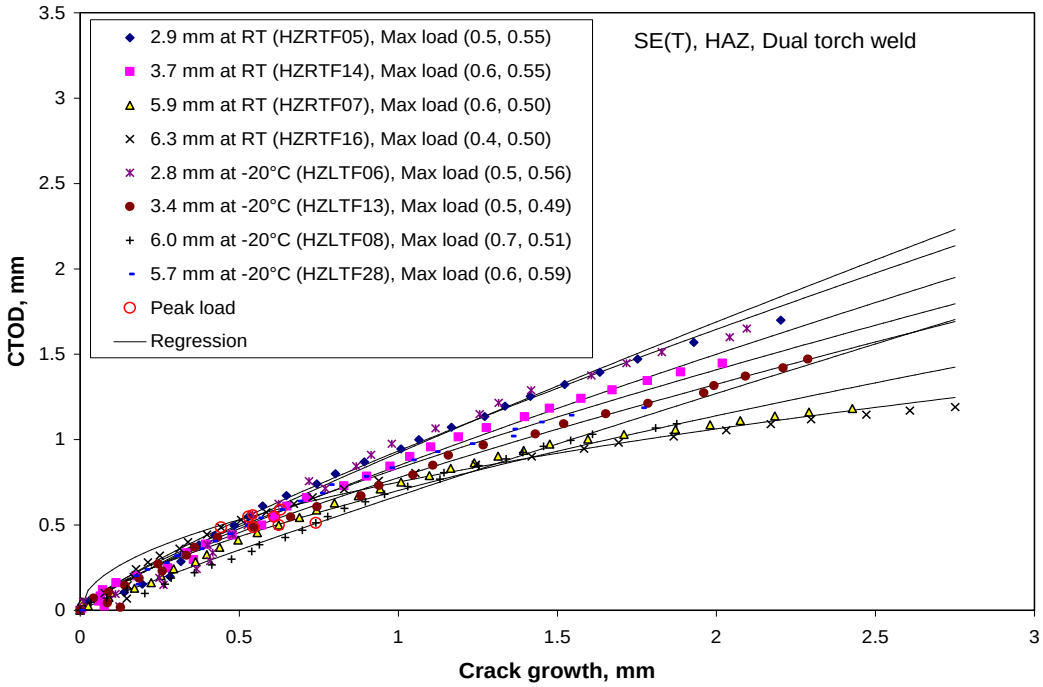


(b)

Figure 13. SE(T) CTOD-resistance curves for single torch (round 1) (a) weld metal and (b) HAZ.

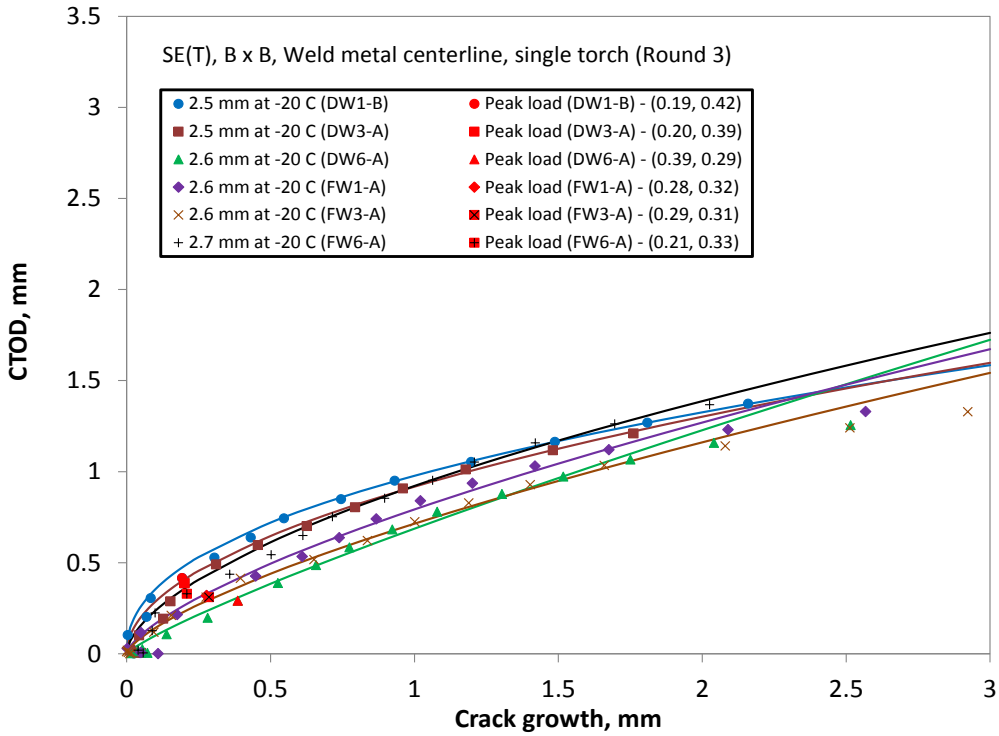


(a)

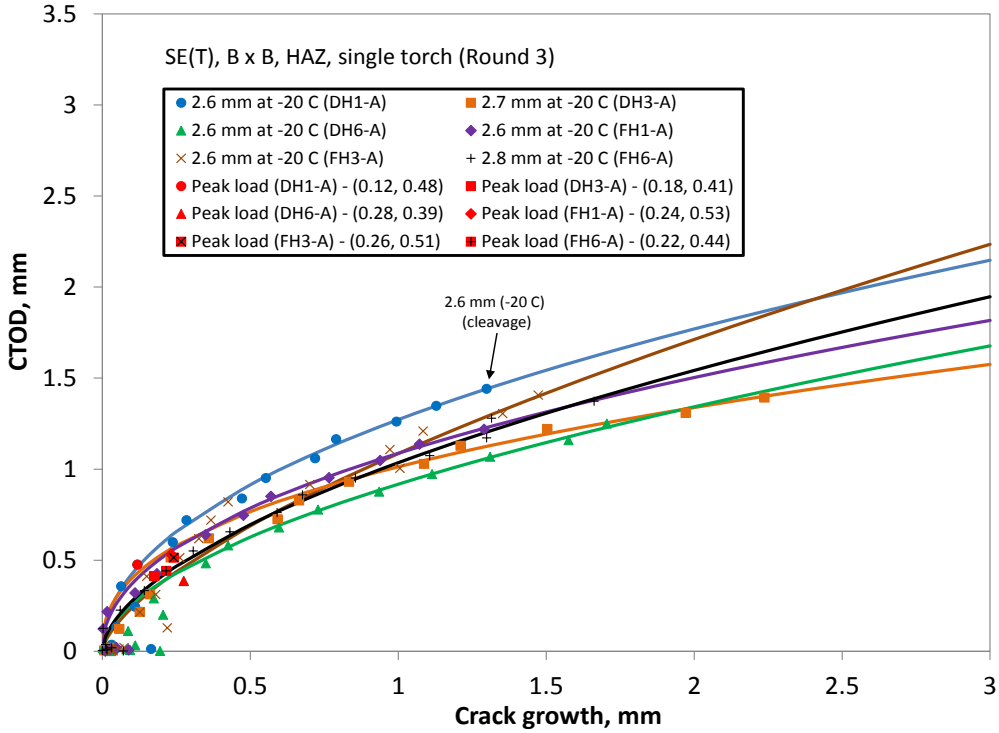


(b)

Figure 14. SE(T) CTOD-resistance curves for dual torch (round 2) (a) weld metal and (b) HAZ.



(a)



(b)

Figure 15. SE(T) CTOD-resistance curves for single torch (round 3) (a) weld metal and (b) HAZ.

4.2.2 SE(B)

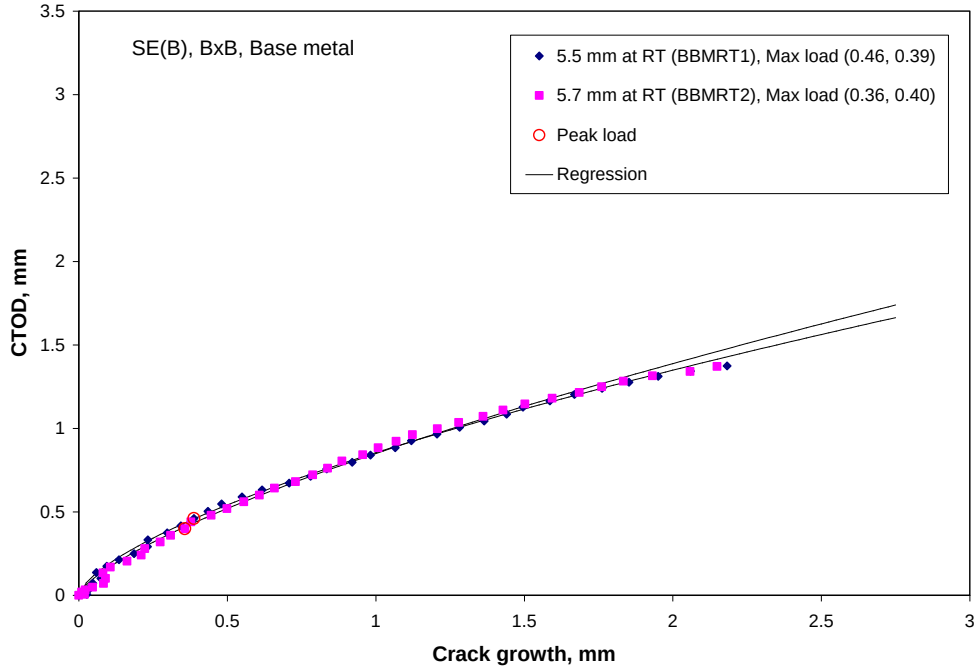


Figure 16. SE(B) CTOD-resistance curves for X100 pipe steel base metal (round 1 and round 2).

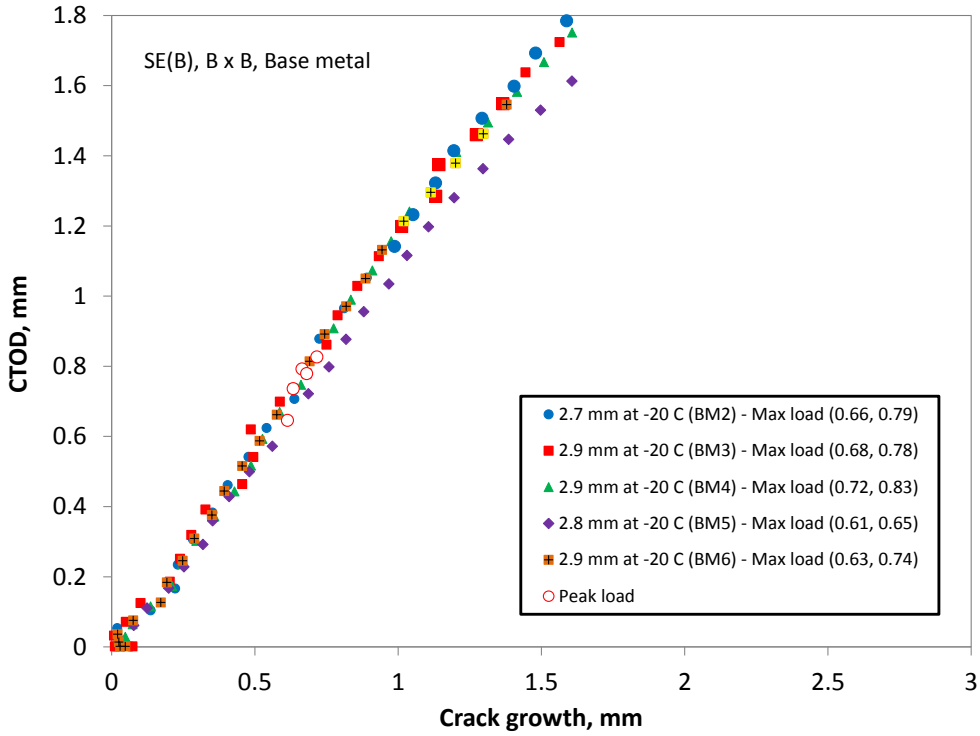
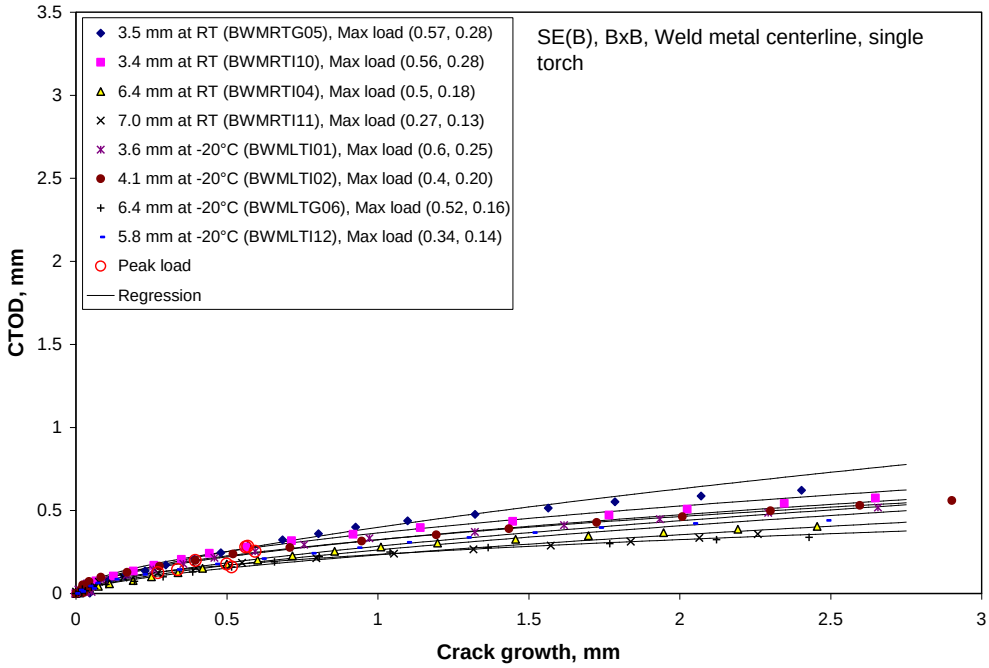
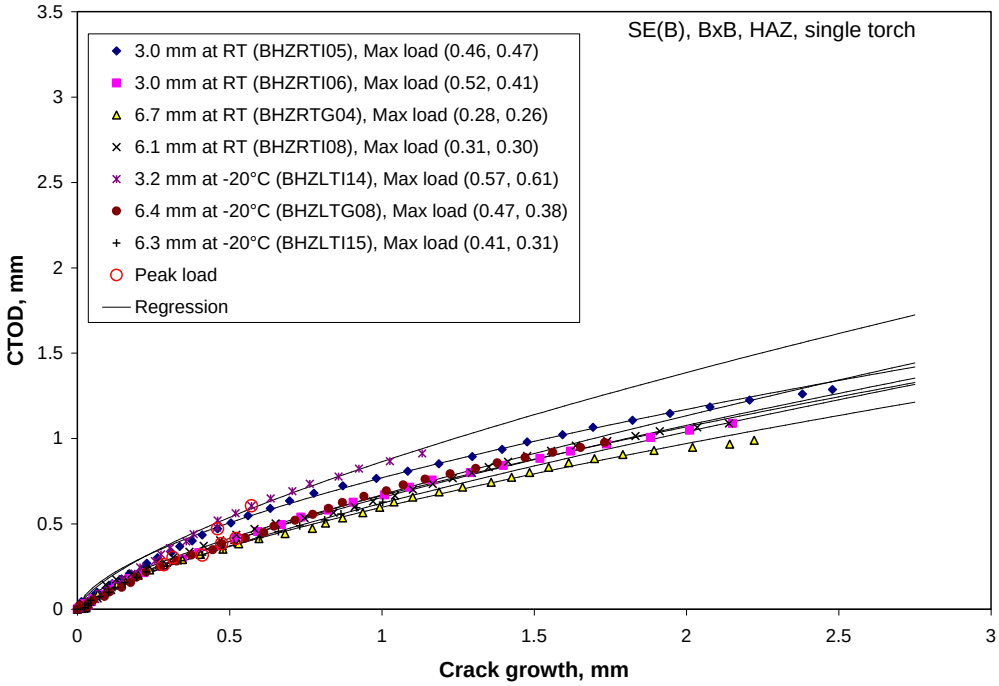


Figure 17. SE(B) CTOD-resistance curves for X100 pipe steel base metal (round 3).

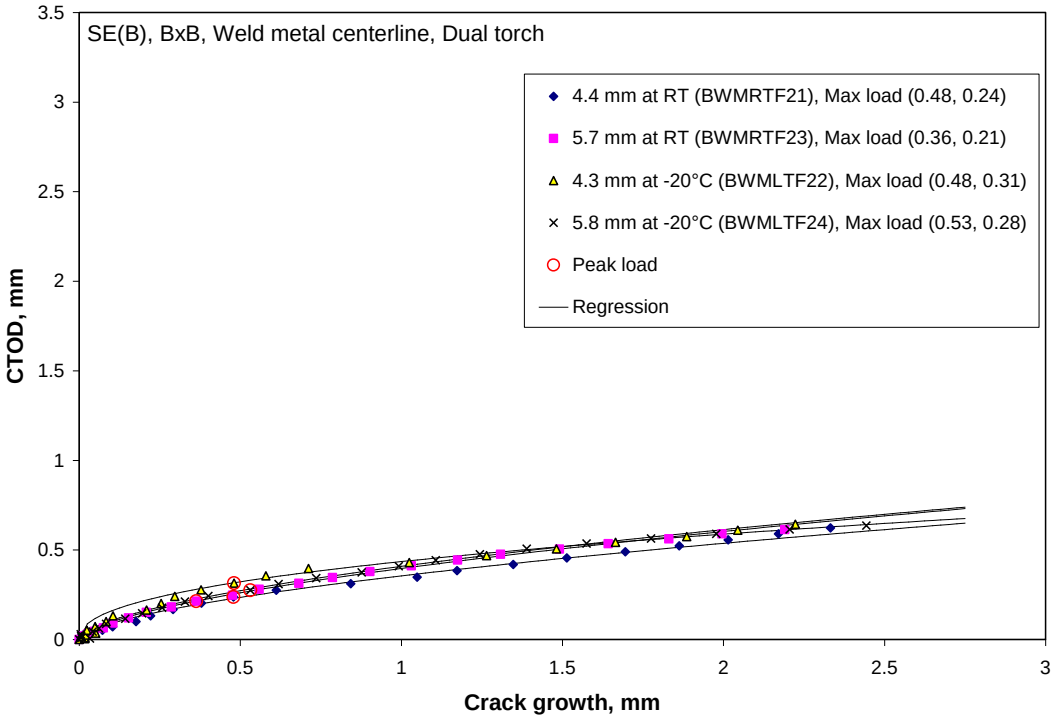


(a)

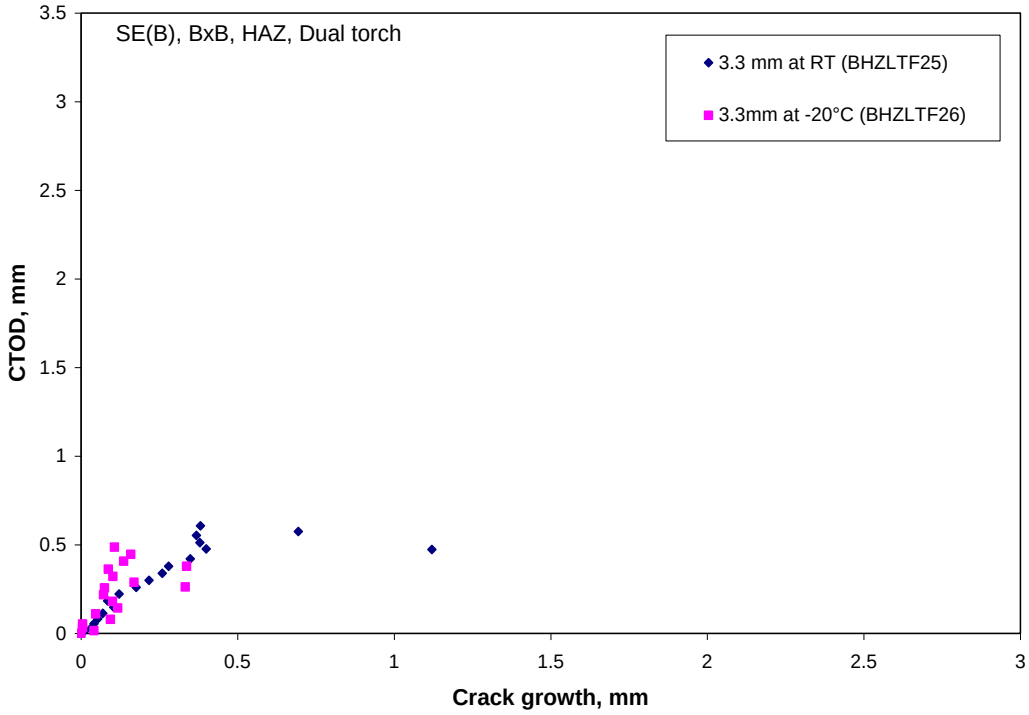


(b)

Figure 18. CTOD-resistance curves for SE(B) single torch (round 1) (a) weld metal and (b) HAZ.

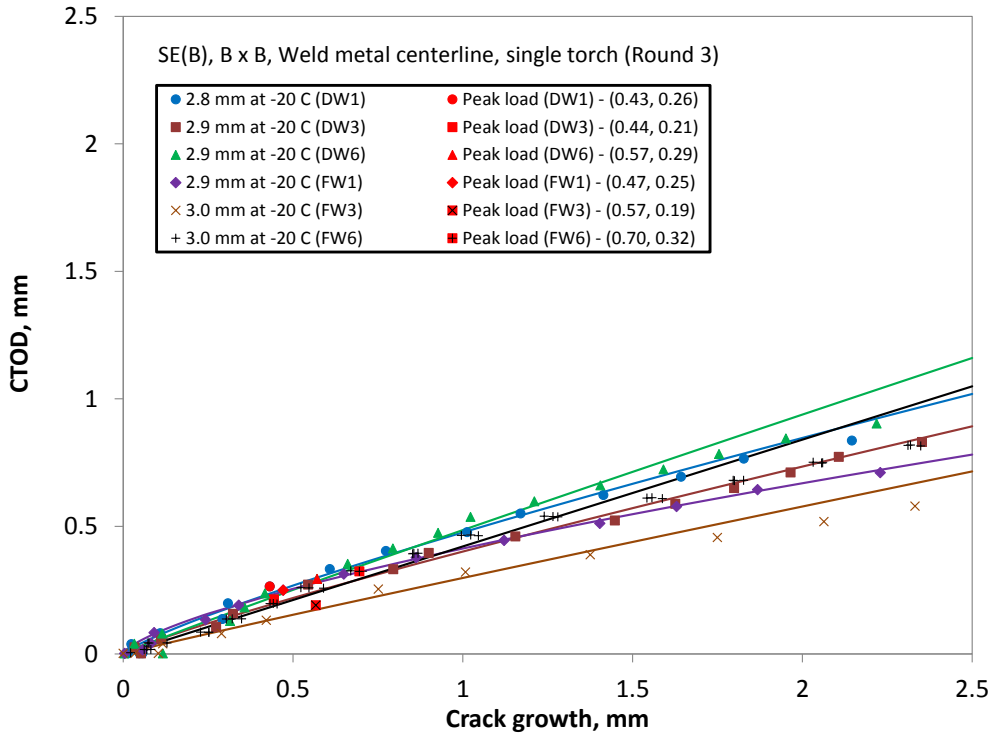


(a)

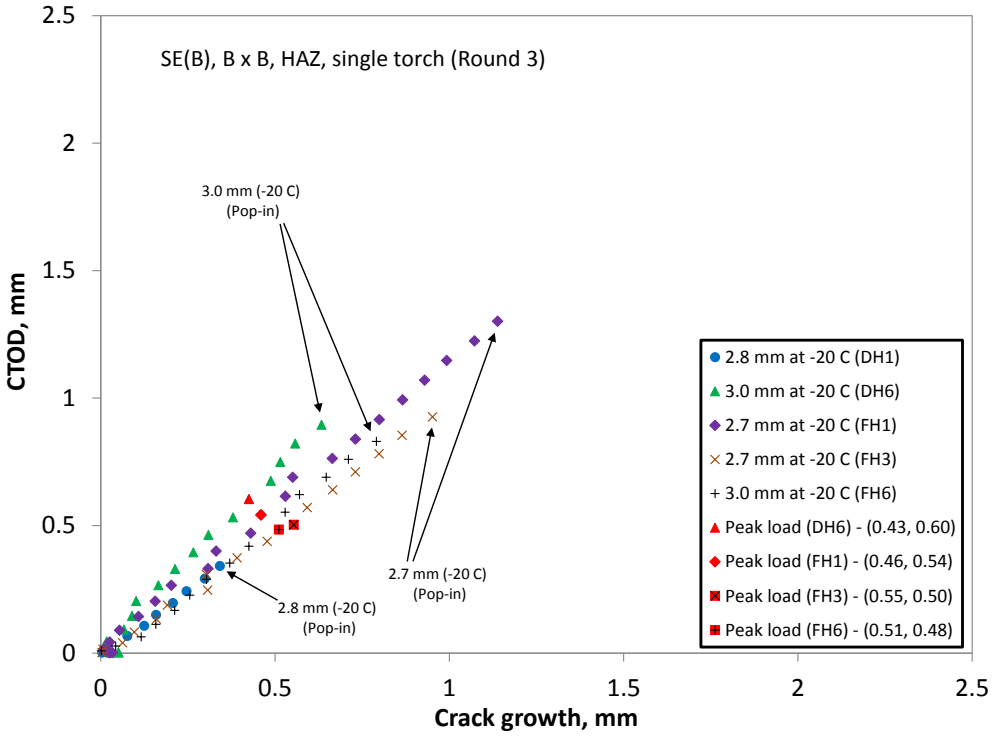


(b)

Figure 19. SE(B) CTOD-resistance curves for dual torch (round 2) (a) weld metal and (b) HAZ.



(a)



(b)

Figure 20. SE(B) CTOD-resistance curves for single torch (round 3) (a) weld metal and (b) HAZ.

4.3 Curve-fit Parameters

This section summarizes regression constants (*C1* and *C2*) of the power law regression (*J* (or CTOD) = $C1 \bullet \Delta a^{C2}$) for SE(T) and SE(B) tests; *J* and CTOD are in kJ/m^2 and mm, respectively.

4.3.1 SE(T)

4.3.1.1 J RESISTANCE

Table 9. Curve-fit parameters for base metal (round 1 and round 2).

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BMRTK06	1313.72	1283.41	42.87	0.786	0.80	0.02	0.999	3.34	3.45	0.16
		K09	1253.10			0.819			0.996	3.56		
	6	BMRTK12	1182.48	1141.32	38.89	0.556	0.58	0.03	0.998	6.42	6.47	0.22
		K13	1105.18			0.580			0.995	6.29		
		K14	1136.29			0.618			0.990	6.71		
-20	3	BMLTK10	1500.36	n/a	n/a	0.856	n/a	n/a	0.995	3.01	n/a	n/a
	6	BMLTK11	1328.13	n/a	n/a	0.463	n/a	n/a	0.993	6.51	n/a	n/a

Table 10. Curve-fit parameters for single torch weld metal centerline (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev. dev.		Individual	Avg.	Std. dev.
RT	3	WMRTK01	540.63	608.38	95.80	0.648	0.66	0.02	0.989	5.31	4.68	0.90
		K22	676.12			0.672			0.998	4.04		
	6	WMRTK11	499.97	496.01	5.59	0.865	0.79	0.11	0.993	8.55	7.96	0.83
		K19	492.06			0.706			0.995	7.38		
-20	3	WMLTK02	476.35	563.92	79.53	0.812	0.76	0.05	0.986	5.01	4.26	0.66
		K15	583.77			0.769			0.997	3.96		
		K23	631.63			0.704			0.992	3.79		
	6	WMLTK12	463.14	474.43	21.51	0.783	0.76	0.04	0.993	7.11	7.01	0.27
		K13	460.91			0.780			0.991	7.22		
		K14	499.24			0.717			0.989	6.71		
-40	3	WMLT4K24	512.49	564.15	73.05	0.930	0.84	0.13	0.971	3.30	3.42	0.17
		K25	615.80			0.740			0.991	3.54		

Table 11. Curve-fit parameters for single torch HAZ (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	HZRTK07	1326.06	1378.61	74.32	0.655	0.66	0.00	0.990	3.72	3.44	0.40
		K21	1431.16			0.656			0.998	3.16		
	6	HZRTK18	1108.03	1081.73	37.20	0.523	0.54	0.02	0.993	6.48	6.54	0.09
		K20	1055.43			0.554			0.987	6.60		
-20	3	K09	1159.19	1237.78	111.14	0.645	0.72	0.10	0.891	3.80	3.64	0.23
		K16	1316.37			0.785			0.986	3.47		
	6	HZLTK05	894.06	948.18	105.91	0.564	0.72	0.13	0.958	7.03	6.62	0.36
		K06	1070.21			0.806			0.972	6.36		
		K17	880.27			0.787			0.990	6.46		
-40	3	HZLT4K26	1400.18	1354.92	64.00	0.668	0.77	0.15	0.980	3.60	3.10	0.70
		K27	1309.67			0.878			0.990	2.61		

Table 12. Curve-fit parameters for dual torch weld metal centerline (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	WMRTF02	669.46	641.27	39.87	0.692	0.70	0.01	0.995	3.99	4.11	0.17
		F09	613.08			0.711			0.997	4.23		
	6	WMRTF04	656.11	649.06	9.97	0.776	0.77	0.01	0.998	5.64	5.72	0.11
		F11	642.01			0.767			0.997	5.79		
-20	3	WMLTF10	463.82	538.18	105.16	0.975	0.87	0.15	0.988	4.07	3.87	0.29
		F102	612.54			0.764			0.997	3.67		
	6	WMLTF03	589.75	647.27	81.34	0.871	0.79	0.12	0.997	5.80	5.81	0.02
		F12	704.79			0.704			0.997	5.82		

Table 13. Curve-fit parameters for dual torch HAZ (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	HZRTF05	1178.66	1132.12	65.82	0.829	0.83	0.00	0.998	3.06	3.36	0.42
		F14	1085.58			0.829			0.994	3.65		
	6	HZRTF07	908.86	940.27	44.42	0.699	0.60	0.14	0.984	5.93	6.10	0.25
		F16	971.68			0.497			0.994	6.28		
-20	3	HZLTF06	1210.12	1120.93	126.13	0.878	0.82	0.08	0.988	2.95	3.20	0.35
		F13	1031.75			0.767			0.995	3.45		
	6	HZLTF08	898.01	1006.41	153.30	0.906	0.83	0.11	0.986	6.12	5.89	0.32
		F28	1114.81			0.750			0.993	5.66		

Table 14. Curve-fit parameters for single torch weld metal centerline (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DW1-B*	1311.89	1239.00	144.73	0.465	0.59	0.16	0.997	2.16	2.39	0.22
		DW3-A	1332.80			0.535			0.990	2.60		
		DW6-A	1072.32			0.763			0.962	2.41		
		FW1-A	1180.53	1175.51	127.59	0.634	0.65	0.03	0.956	2.51	2.49	0.04
		FW3-A	1045.49			0.683			0.980	2.44		
		FW6-A	1300.52			0.627			0.978	2.53		

* Specimen not side grooved (plane sided). Data from specimen DW1-A could not be analyzed.

Table 15. Curve-fit parameters for single torch HAZ (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DH1-A	1663.40	1529.03	118.37	0.580	0.522	0.09	0.967	2.47	2.48	0.07
		DH3-A	1483.49			0.419			0.967	2.55		
		DH6-A	1440.19			0.566			0.992	2.41		
		FH1-A	1586.26	1581.22	88.00	0.541	0.552	0.04	0.989	2.46	2.46	0.03
		FH3-A	1666.59			0.519			1.000	2.42		
		FH6-A	1490.81			0.595			0.873	2.49		

4.3.1.2 CTOD RESISTANCE

Table 16. Curve-fit parameters for base metal

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BMRTK06	1.34	1.30	0.06	0.778	0.79	0.02	0.998	3.34	3.45	0.16
		K09	1.25			0.810			0.994	3.56		
	6	BMRTK12	1.27	1.18	0.08	0.575	0.60	0.03	0.996	6.42	6.47	0.22
		K13	1.12			0.597			0.992	6.29		
		K14	1.16			0.628			0.986	6.71		
-20	3	BMLTK10	1.41	n/a	n/a	0.847	n/a	n/a	0.994	3.01	n/a	n/a
	6	BMLTK11	1.32	n/a	n/a	0.459	n/a	n/a	0.990	6.51	n/a	n/a

Table 17. Curve-fit parameters for single torch weld metal centerline (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	WMRTK01	0.41	0.47	0.08	0.682	0.68	0.00	0.990	5.31	4.68	0.90
		K22	0.53			0.687			0.998	4.04		
	6	WMRTK11	0.41	0.39	0.04	0.947	0.86	0.12	0.989	8.55	7.96	0.83
		K19	0.36			0.779			0.995	7.38		
-20	3	WMLTK02	0.34	0.41	0.06	0.847	0.79	0.06	0.985	5.01	4.26	0.66
		K15	0.43			0.809			0.997	3.96		
		K23	0.46			0.724			0.993	3.79		
	6	WMLTK12	0.32	0.33	0.01	0.873	0.84	0.05	0.995	7.11	7.01	0.27
		K13	0.32			0.863			0.991	7.22		
		K14	0.34			0.775			0.989	6.71		
-40	3	WMLT4K24	0.36	0.40	0.06	0.960	0.86	0.14	0.973	3.30	3.42	0.17
		K25	0.44			0.758			0.992	3.54		

Table 18. Curve-fit parameters for single torch HAZ (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	HZRTK07	1.03	1.08	0.07	0.649	0.65	0.00	0.987	3.72	3.44	0.40
		K21	1.13			0.644			0.998	3.16		
	6	HZRTK18	0.85	0.83	0.04	0.527	0.54	0.02	0.990	6.48	6.54	0.09
		K20	0.80			0.556			0.982	6.60		
-20	3	K09	0.88	0.94	0.07	0.664	0.73	0.09	0.900	3.80	3.64	0.23
		K16	0.99			0.789			0.984	3.47		
	6	HZLTK05	0.63	0.69	0.08	0.581	0.74	0.14	0.955	7.03	6.62	0.36
		K06	0.78			0.825			0.973	6.36		
		K17	0.64			0.821			0.988	6.46		
-40	3	HZLT4K26	1.03	1.00	0.04	0.673	0.79	0.16	0.981	3.60	3.10	0.70
		K27	0.97			0.904			0.991	2.61		

Table 19. Curve-fit parameters for dual torch weld metal centerline (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	WMRTF02	0.52	0.50	0.03	0.708	0.72	0.02	0.995	3.99	4.11	0.17
		F09	0.48			0.733			0.997	4.23		
	6	WMRTF04	0.50	0.50	0.01	0.808	0.81	0.00	0.998	5.64	5.72	0.11
		F11	0.49			0.804			0.997	5.79		
-20	3	WMLTF10	0.34	0.40	0.08	1.014	0.90	0.16	0.989	4.07	3.87	0.29
		F102	0.45			0.784			0.996	3.67		
	6	WMLTF03	0.43	0.48	0.06	0.908	0.82	0.13	0.995	5.80	5.81	0.02
		F12	0.52			0.731			0.998	5.82		

Table 20. Curve-fit parameters for dual torch HAZ (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	HZRTF05	0.93	0.89	0.06	0.818	0.82	0.00	0.996	3.06	3.36	0.42
		F14	0.85			0.825			0.992	3.65		
	6	HZRTF07	0.70	0.73	0.03	0.700	0.60	0.14	0.978	5.93	6.10	0.25
		F16	0.75			0.501			0.991	6.28		
-20	3	HZLTF06	0.92	0.85	0.10	0.873	0.82	0.07	0.985	2.95	3.20	0.35
		F13	0.78			0.769			0.996	3.45		
	6	HZLTF08	0.67	0.75	0.11	0.922	0.84	0.11	0.981	6.12	5.89	0.32
		F28	0.83			0.761			0.990	5.66		

Table 21. Curve-fit parameters for single torch weld metal centerline (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DW1-B*	0.977	0.86	0.15	0.440	0.48	0.07	0.997	2.16	2.39	0.22
		DW3-A	0.917			0.505			0.984	2.60		
		DW6-A	0.687			0.838			0.976	2.40		
		FW1-A	0.793	0.81	0.10	0.680	0.57	0.09	0.962	2.50	2.50	0.05
		FW3-A	0.714			0.701			0.974	2.45		
		FW6-A	0.921			0.590			0.981	2.55		

* Specimen not side-grooved (plane-sided). Data from specimen DW1-A could not be analyzed.

Table 22. Curve-fit parameters for single torch HAZ (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DH1-A	1.272	1.07	0.18	0.477	0.48	0.07	1.000	2.47	2.46	0.09
		DH3-A	1.013			0.402			0.961	2.55		
		DH6-A	0.917			0.549			0.995	2.37		
		FH1-A	1.087	1.07	0.03	0.467	0.57	0.09	0.972	2.46	2.45	0.04
		FH3-A	1.086			0.657			0.864	2.40		
		FH6-A	1.035			0.575			0.937	2.48		

4.3.2 SE(B)

4.3.2.1 J RESISTANCE

Table 23. Curve-fit parameters for base metal

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	6	BBMRT1	1121.07	1122.66	2.25	0.678	0.70	0.04	0.999	5.43	5.59	0.24
		T2	1124.26			0.729			0.997	5.76		
-20	3	BM2	2117.42	1951.10	361.04	0.285	0.38	0.30	0.911	2.44	2.68	0.15
		BM3	2109.26			0.254			0.852	2.76		
		BM4	2166.84			0.170			1.000	2.75		
		BM5	1410.89			0.818			0.998	2.62		
		BM6	*			*			*	2.81		

* Experimental data for specimen BM6 could not be fitted (no data points fall between the exclusion lines).

Table 24. Curve-fit parameters for single torch weld metal centerline (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BWMRTG05	550.03	526.25	33.63	0.680	0.61	0.09	0.991	3.61	3.58	0.05
		I10	502.47			0.549			0.992	3.55		
	6	BWMRTI04	388.67	370.56	25.60	0.654	0.57	0.12	0.983	6.45	6.72	0.38
		I11	352.46			0.481			0.997	6.98		
-20	3	BWMLTI01	447.57	451.21	5.14	0.573	0.56	0.02	0.991	3.69	3.95	0.37
		I02	454.84			0.540			0.999	4.21		
	6	BWMLTG06	343.84	379.24	50.07	0.624	0.63	0.01	0.977	6.41	6.13	0.41
		I12	414.64			0.643			0.999	5.84		

Table 25. Curve-fit parameters for single torch HAZ (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BHZRTI05	1050.85	972.24	111.17	0.631	0.69	0.08	0.999	3.20	3.20	0.00
		~I06	893.64			0.743			0.997	3.20		
	6	BHZRTG04	889.62	933.15	61.56	0.724	0.71	0.01	0.996	6.76	6.43	0.46
		~I08	976.67			0.706			0.996	6.11		
-20	3	~I14	1180.33			0.700			0.989	3.38	n/a	n/a
	6	BHZLTG08	989.91	950.63	55.55	0.779	0.77	0.01	0.996	6.42	6.37	0.08
		~I15	911.35			0.758			0.996	6.31		

Table 26. Curve-fit parameters for dual torch weld metal centerline (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BWMRTF21	501.67	n/a	n/a	0.617	n/a	n/a	0.995	4.47	n/a	n/a
	6	BWMRTF23	576.90	n/a	n/a	0.627	n/a	n/a	0.999	5.76	n/a	n/a
-20	3	BWMLTF22	611.81	n/a	n/a	0.459	n/a	n/a	0.989	4.34	n/a	n/a
	6	BWMLTF24	595.51	n/a	n/a	0.607	n/a	n/a	0.998	5.82	n/a	n/a

Table 27. Curve-fit parameters for single torch weld metal centerline (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DW1	634.46	651.81	66.73	0.848	0.91	0.06	0.986	2.79	2.80	0.06
		DW3	595.47			0.907			0.992	2.74		
		DW6	725.50			0.963			0.988	2.86		
		FW1	601.64	542.62	94.43	0.721	0.90	0.16	0.996	2.90	2.83	0.09
		FW3	433.71			0.985			0.977	2.84		
		FW6	592.52			1.007			0.981	2.73		

Table 28. Curve-fit parameters for single torch HAZ (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DH1	*	n/a	n/a	*	n/a	n/a	*	3.03	2.96	0.10
		DH6	*			*			*	2.88		
		FH1	*	1443.17	n/a	*	1.16	n/a	*	2.70		
		FH3	1443.17			1.16			0.997	2.73		
		FH6	*			*			*	2.85		

* Experimental data for specimens DH1, DH6, FH1 and FH6 cannot be fitted (no data points fall between the exclusion lines).

4.3.2.2 CTOD RESISTANCE

Table 29. Curve-fit parameters for base metal

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	6	BBMRT1	0.85	0.85	0.00	0.658	0.68	0.04	0.999	5.43	5.59	0.24
		T2	0.85			0.708			0.995	5.76		
-20	3	BM2	1.28	1.23	0.12	0.561	0.65	0.23	0.860	2.44	2.68	0.15
		BM3	1.30			0.483			0.846	2.76		
		BM4	1.28			0.561			0.837	2.76		
		BM5	1.05			0.987			0.997	2.63		
		BM6	1.19			0.799			0.999	2.81		

Table 30. Curve-fit parameters for single torch weld metal centerline (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BWMRTG05	0.40	0.38	0.02	0.659	0.59	0.09	0.989	3.61	3.58	0.05
		I10	0.37			0.529			0.990	3.55		
	6	BWMRTI04	0.26	0.25	0.02	0.634	0.55	0.12	0.980	6.45	6.72	0.38
		I11	0.24			0.464			0.996	6.98		
-20	3	BWMLTI01	0.32	0.32	0.00	0.552	0.53	0.03	0.989	3.69	3.95	0.37
		I02	0.32			0.516			0.999	4.21		
	6	BWMLTG06	0.23	0.26	0.04	0.605	0.61	0.01	0.973	6.41	6.13	0.41
		I12	0.28			0.623			0.999	5.84		

Table 31. Curve-fit parameters for single torch HAZ (round 1)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BHZRTI05	0.77	0.71	0.08	0.605	0.66	0.08	0.998	3.20	3.20	0.00
		I06	0.65			0.718			0.996	3.20		
	6	BHZRTG04	0.60	0.63	0.05	0.701	0.69	0.01	0.996	6.76	6.43	0.46
		I08	0.67			0.682			0.996	6.11		
-20	3	I14	0.86			0.682			0.987	3.38	n/a	n/a
	6	BHZLTG08	0.67	0.65	0.04	0.758	0.75	0.01	0.995	6.42	6.37	0.08
		I15	0.62			0.743			0.996	6.31		

Table 32. Curve-fit parameters for dual torch weld metal centerline (round 2)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
RT	3	BWMRTF21	0.36	n/a	n/a	0.595	n/a	n/a	0.995	4.47	n/a	n/a
	6	BWMRTF23	0.40	n/a	n/a	0.604	n/a	n/a	0.998	5.76	n/a	n/a
-20	3	BWMLTF22	0.44	n/a	n/a	0.434	n/a	n/a	0.988	4.34	n/a	n/a
	6	BWMLTF24	0.41	n/a	n/a	0.585	n/a	n/a	0.997	5.82	n/a	n/a

Table 33. Curve-fit parameters for single torch weld metal centerline (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DW1	0.48	0.45	0.05	0.830	0.88	0.06	0.987	2.79	2.80	0.06
		DW3	0.40			0.873			0.987	2.74		
		DW6	0.49			0.951			0.983	2.86		
		FW1	0.41	0.38	0.07	0.696	0.88	0.16	0.994	2.90	2.83	0.09
		FW3	0.30			0.957			0.971	2.84		
		FW6	0.42			0.996			0.975	2.73		

Table 34. Curve-fit parameters for single torch HAZ (round 3)

Temp (°C)	Target a_o (mm)	ID	C1			C2			round 2	a_{oq} (mm)		
			Individual	Avg.	Std. dev.	Individual	Avg.	Std. dev.		Individual	Avg.	Std. dev.
-20	3	DH1	*	n/a	n/a	*	n/a	n/a	*	3.03	2.96	0.10
		DH6	*			*			*	2.89		
		FH1	1.15	1.06	0.08	0.976	1.00	0.10	0.998	2.70	2.76	0.08
		FH3	1.00			1.110			0.997	2.73		
		FH6	1.03			0.918			0.996	2.85		

* Experimental data for specimens DH1 and DH6 could not be fitted (no data points fell between the exclusion lines).

5 POST-TEST ANALYSIS

5.1 Crack Growth Estimation

The figures in this section compare unloading-compliance-predicted crack lengths (initial length a_o and final length a_f) to post-test measurements on the fracture surfaces of broken-open specimens that were heat tinted after testing.

5.1.1 SE(T)

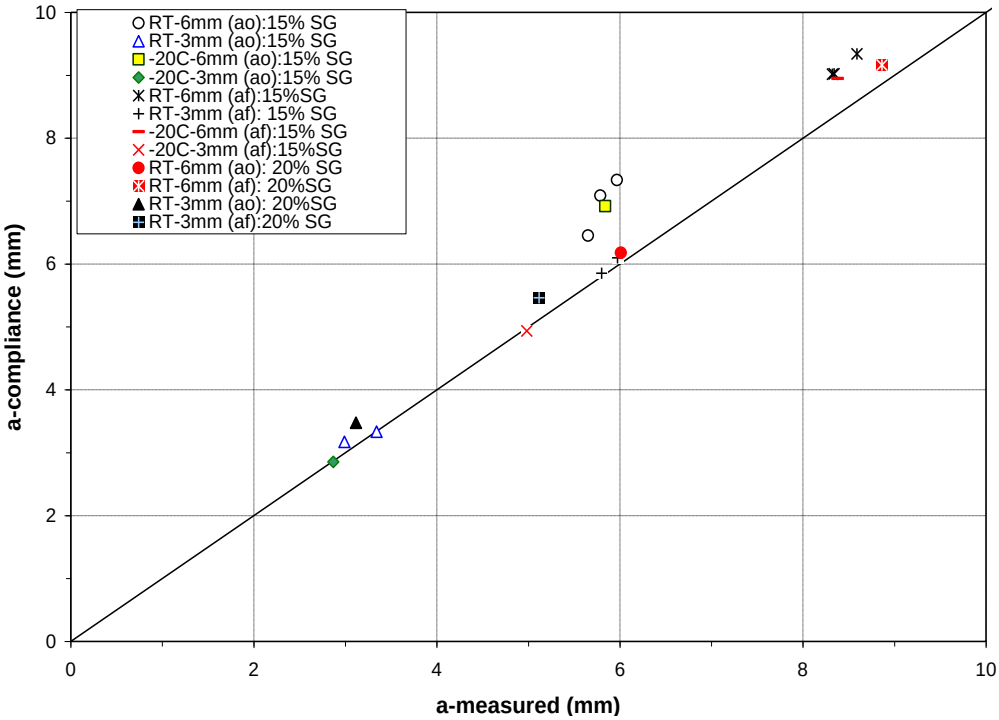
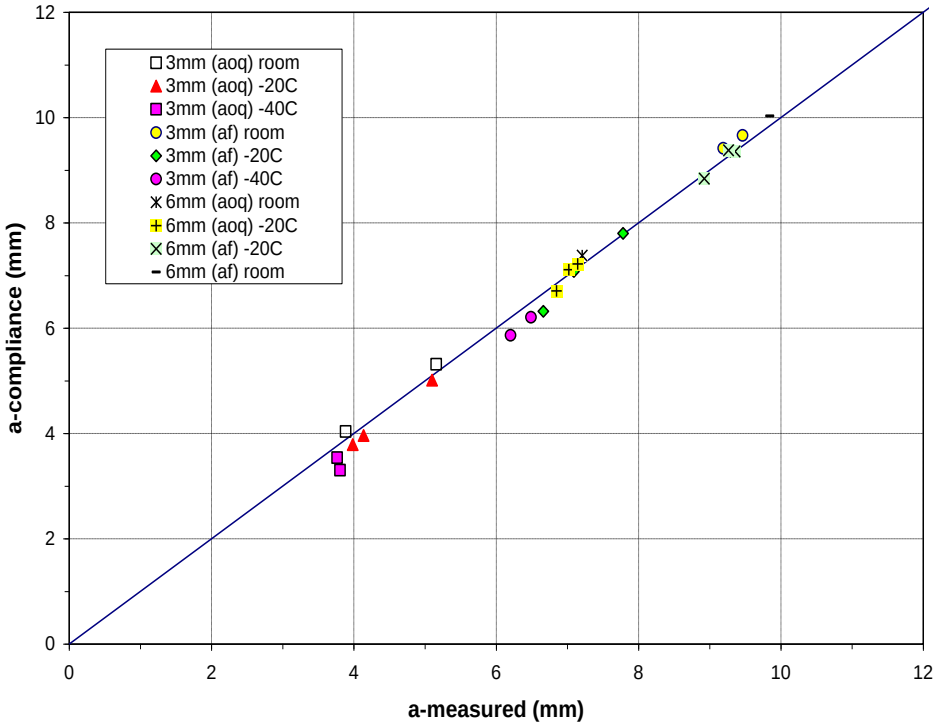
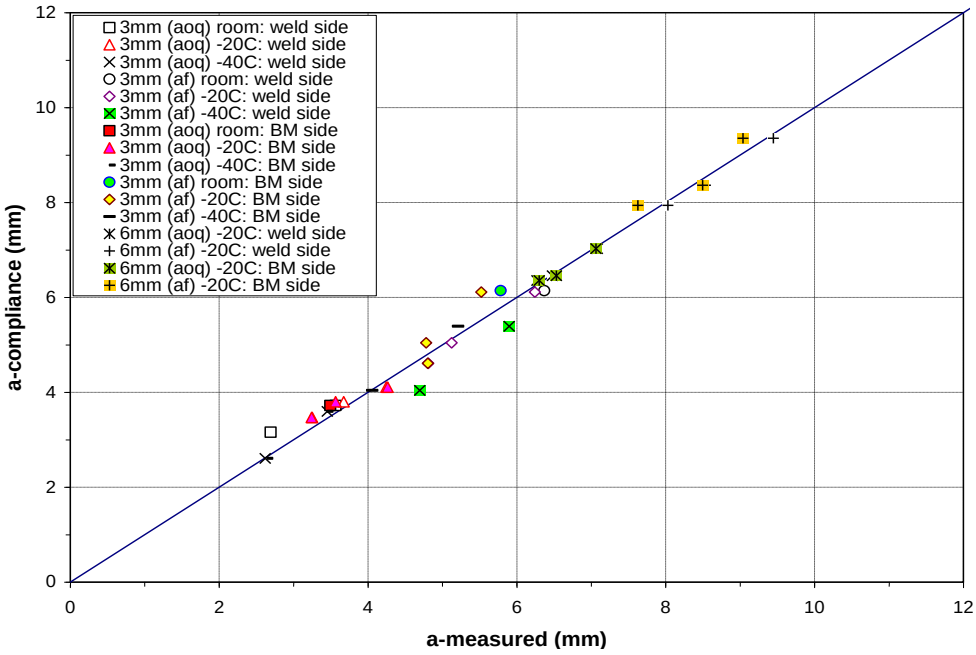


Figure 21. Comparison between measured and unloading-compliance-predicted crack lengths for SE(T) base metal tests.
(The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

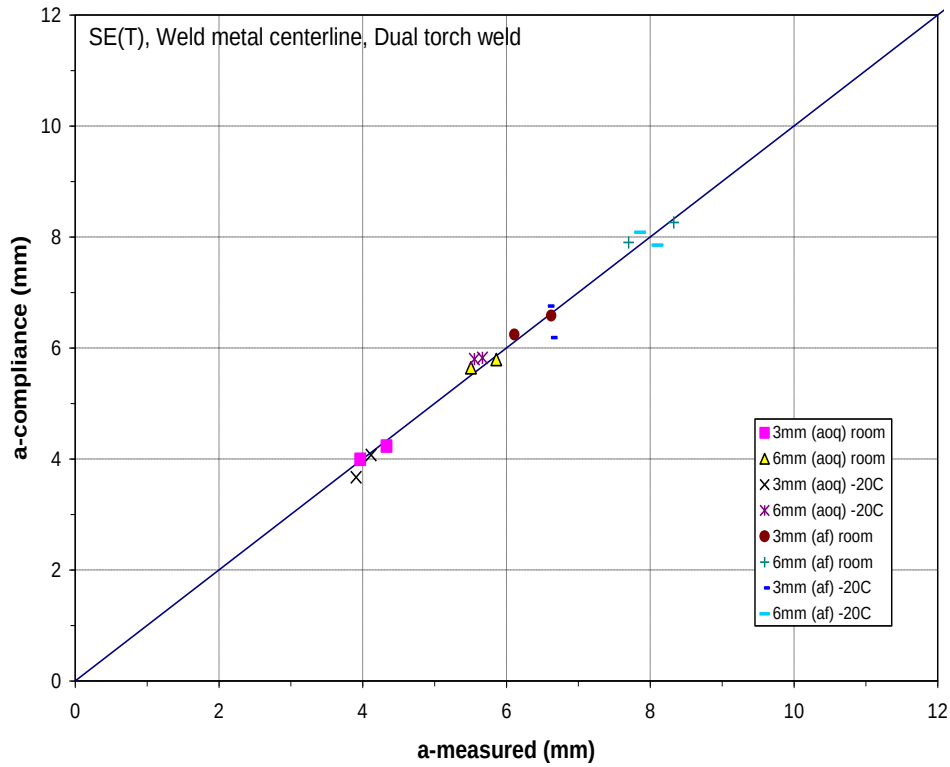


(a)

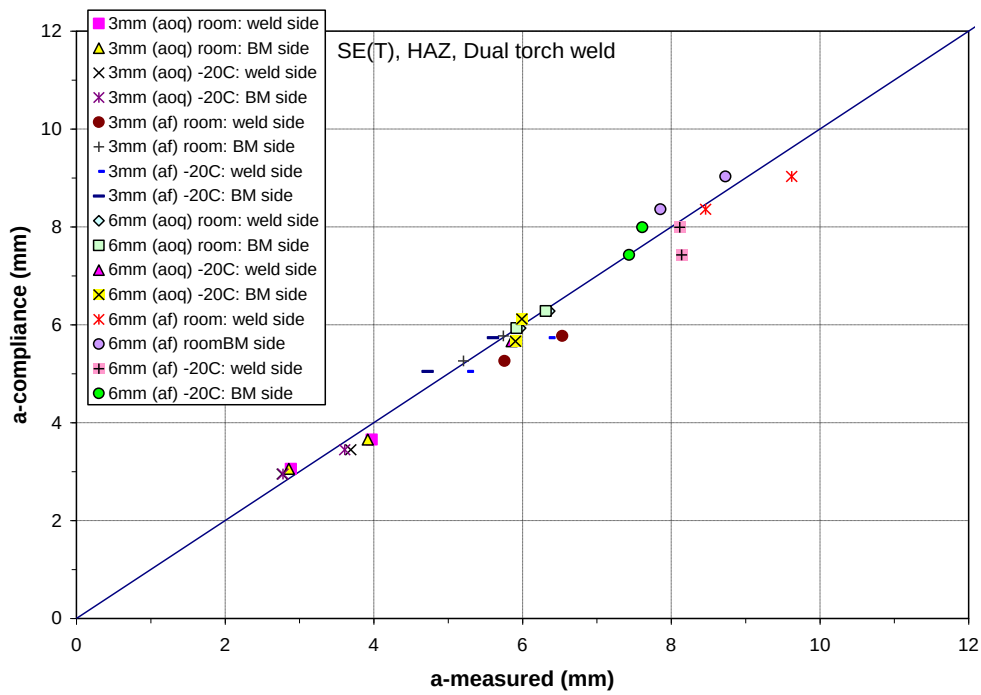


(b)

Figure 22. Comparison between measured and unloading-compliance-predicted crack lengths for SE(T) single torch (round 1) (a) weld metal and (b) HAZ. (The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

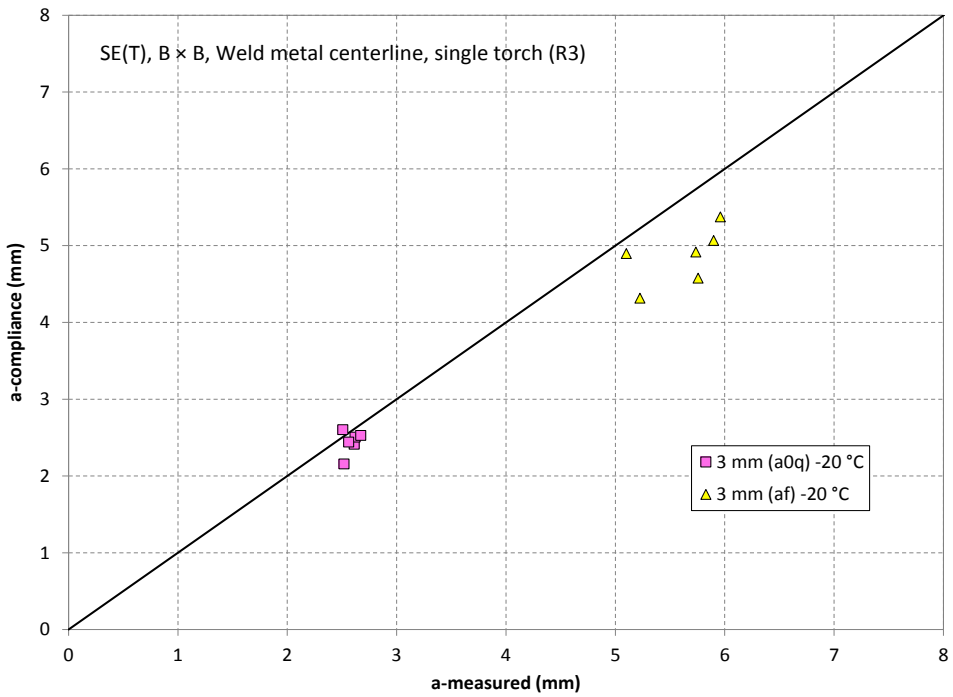


(a)

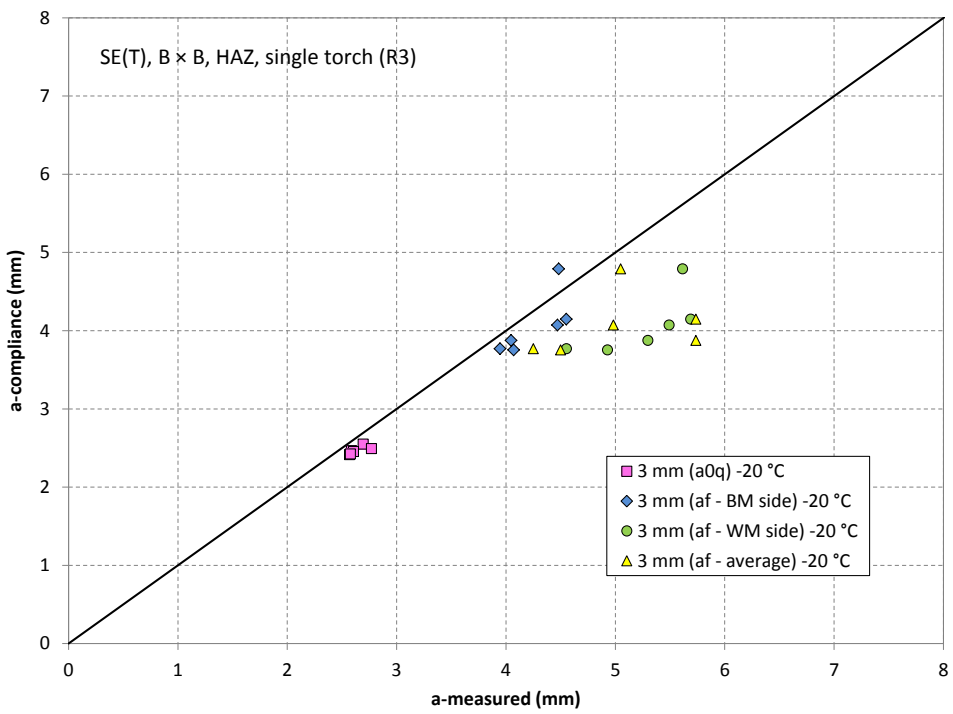


(b)

Figure 23. Comparison between measured and unloading-compliance-predicted crack lengths for SE(T) dual torch (round 2) (a) weld metal and (b) HAZ. (The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)



(a)



(b)

Figure 24. Comparison between measured and unloading-compliance-predicted crack lengths for SE(T) single torch (round 3) (a) weld metal and (b) HAZ. Note that for HAZ tests, compliance-based predictions of final crack size are much closer to the measurements performed on the BM side than on the WM side. (The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

5.1.2 SE(B)

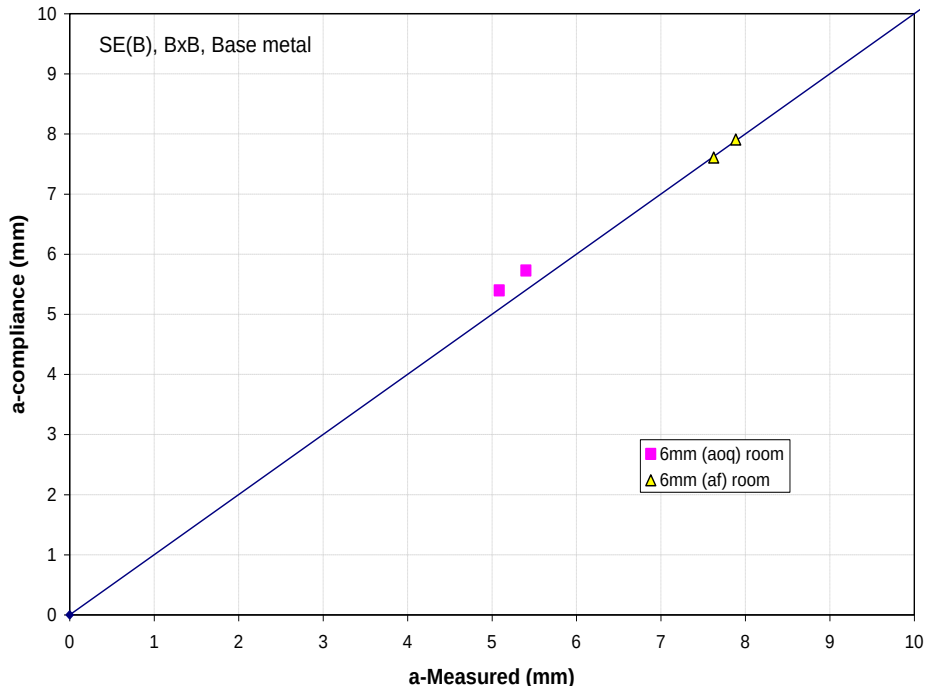


Figure 25. Comparison between measured and unloading-compliance-predicted crack lengths for SE(B) base metal.
(The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

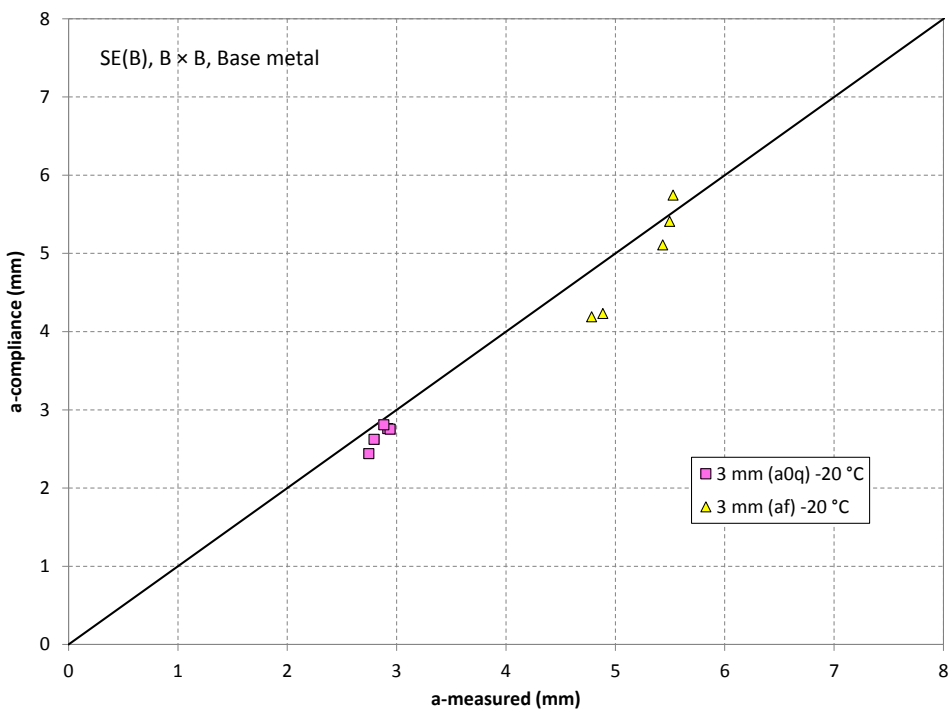
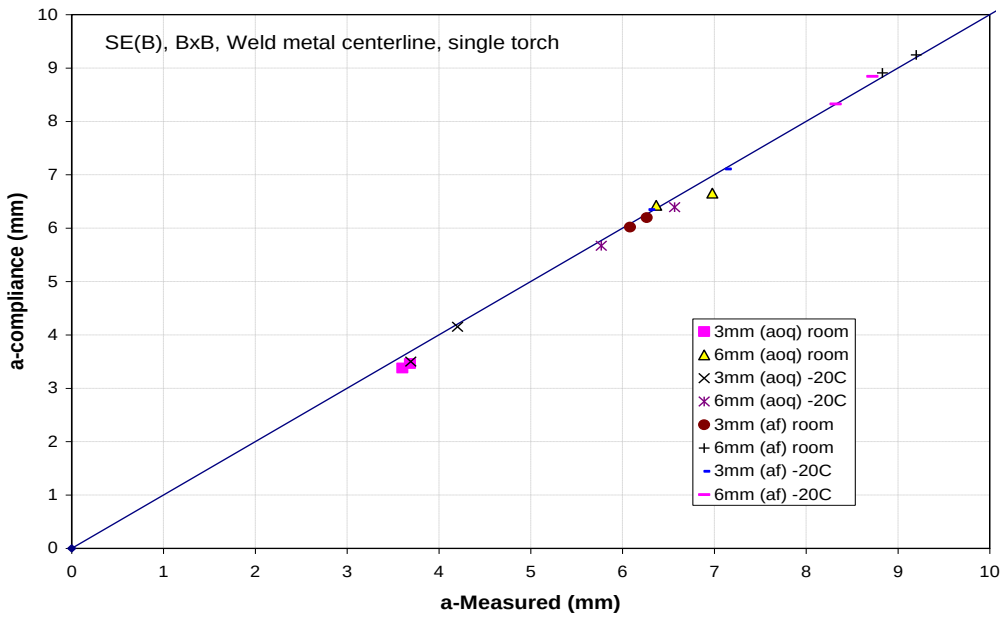
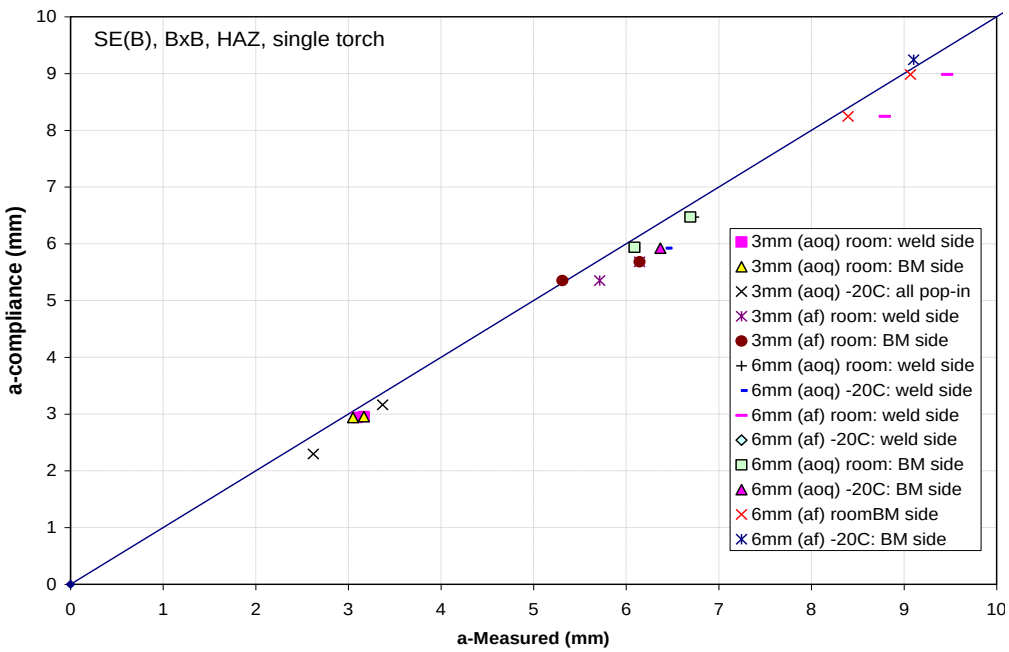


Figure 26. Comparison between measured and unloading-compliance-predicted crack lengths for SE(B) base metal on Pipe A (round 3).
(The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)



(a)



(b)

Figure 27. Comparison between measured and unloading-compliance-predicted crack lengths for SE(B) single torch (round 1) (a) weld metal and (b) HAZ. (The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

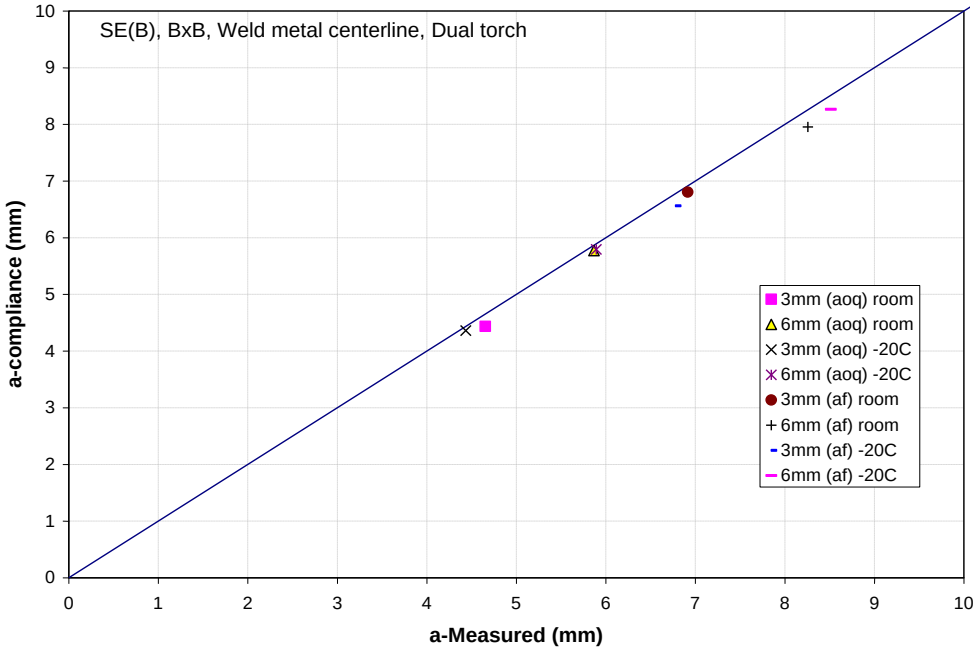
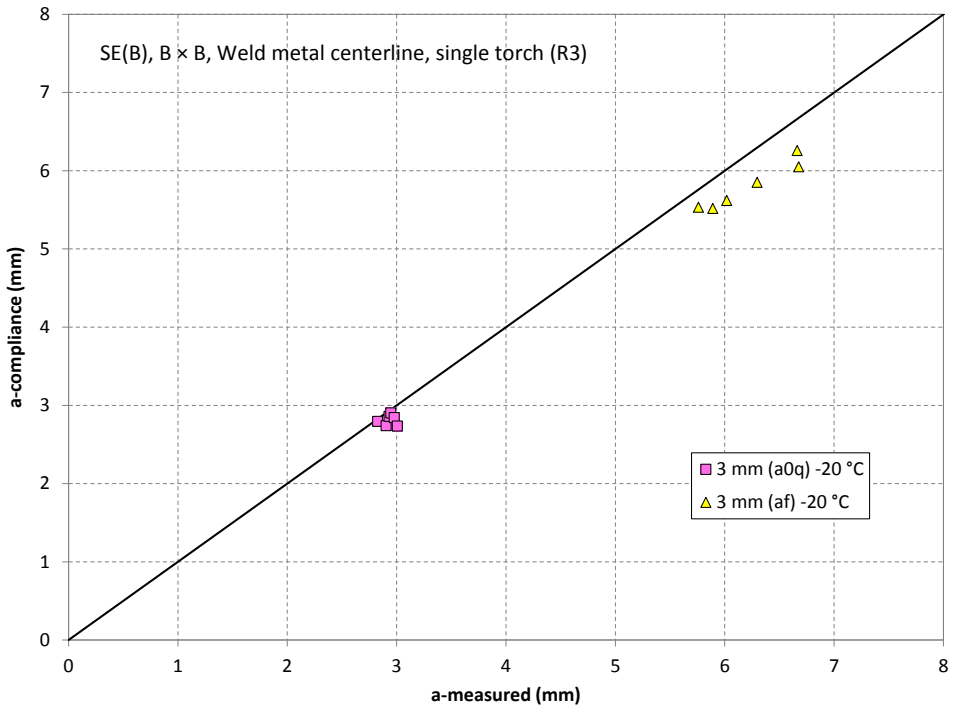
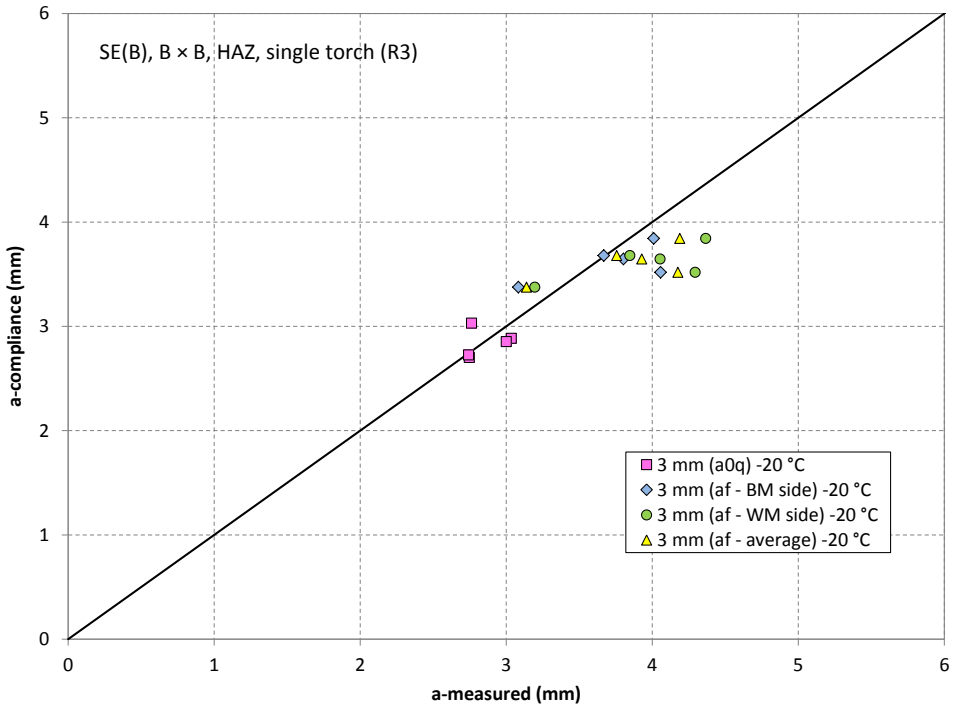


Figure 28. Comparison between measured and unloading-compliance-predicted crack lengths for SE(B) dual torch (round 2) weld metal.
(The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)



(a)



(b)

Figure 29. Comparison between measured and unloading-compliance-predicted crack lengths for SE(B) single torch (round 3) (a) weld metal and (b) HAZ. (The line represents a 1:1 relationship between the predicted value and the measured value of the crack length as opposed to a fit of the data.)

5.2 Crack Size Qualification

This section summarizes the crack size qualification according to the requirements of the following standards:

- ASTM E 1820 – 11[5]:
  - Clause 9.1.4.1 (original crack size): none of the nine physical measurements of initial crack size shall differ by more than 0.05B from the average a_o.
  - Clause 9.1.4.2 (final crack size): none of the nine physical measurements of final physical crack size shall differ by more than 0.05B from the average a_p.
  - Clause 9.1.5.1 (crack extension): none of the nine physical measurements of crack extension shall be less than 50 % of the average crack extension.
  - Clause 9.1.5.2 (crack extension prediction): the difference between the unloading compliance-predicted crack extension and the measurement shall not exceed 0.15 Δa_p for crack extensions less than 0.2B_o and the difference shall not exceed 0.03B_o thereafter.
- BS 7448: Part 2: 1991[6]:
  - Clause 12.4.1 (original crack size): no two of the inner seven crack length measurements shall differ by more than 0.2a_o for welds.

5.2.1 SE(T)

Table 35. Assessment of crack qualification for base metal

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	BMRTK06	pass	pass	pass	pass	pass
		K09	pass	pass	pass	pass	pass
	6	BMRTK12	pass	pass	pass	pass	pass
		K13	pass	pass	pass	pass	pass
		K14	pass	pass	pass	pass	pass
-20	3	BMLTK10	pass	pass	pass	pass	pass
	6	BMLTK11	pass	pass	pass	pass	pass

Table 36. Assessment of crack qualification for weld metal centerline - single torch (round 1)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	WMRTK01	fail	pass	pass	pass	fail
		K22	fail	pass	pass	pass	pass
	6	WMRTK11	pass	*	*	*	pass
		K19	pass	pass	pass	pass	pass
-20	3	WMLTK02	fail	pass	pass	pass	pass
		K15	fail	pass	pass	pass	pass
		K23	fail	pass	pass	pass	fail
	6	WMLTK12	pass	pass	pass	pass	pass
		K13	pass	pass	pass	pass	pass
		K14	pass	pass	pass	pass	pass
-40	3	WMLT4K24	fail	pass	pass	pass	fail
		K25	fail	fail	pass	pass	fail

* No data available on final crack size of specimens WMRTK11 and HZRTK21 because of ductile instability after extensive tearing (attempt to derive R curve for large crack growth)

Table 37. Assessment of crack qualification for HAZ [single torch (round 1)], based on crack measurements on the weld metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	HZRTK07	fail	pass	pass	fail	fail
		K21	pass	*	*	*	pass
	6	HZRTK18	pass	pass	pass	pass	pass
		K20	pass	pass	pass	fail	pass
-20	3	K09	fail	pass	pass	fail	fail
		K16	pass	pass	pass	pass	pass
	6	HZLTK05	pass	pass	pass	pass	pass
		K06	pass	pass	pass	pass	pass
		K17	pass	pass	pass	pass	pass
-40	3	HZLT4K26	pass	pass	pass	fail	pass
		K27	pass	pass	pass	fail	pass

* No data available on final crack size of specimens WMRTK11 and HZRTK21 because of ductile instability after extensive tearing (attempt to derive R curve for large crack growth)

Table 38. Assessment of crack qualification for HAZ [single torch (round 1)], based on crack measurements on the base metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	HZRTK07	fail	fail	pass	pass	fail
		K21	pass	*	*	*	pass
	6	HZRTK18	pass	fail	pass	fail	pass
		K20	pass	fail	pass	pass	pass
-20	3	K09	fail	fail	pass	pass	fail
		K16	pass	pass	pass	pass	pass
	6	HZLTK05	pass	fail	pass	fail	pass
		K06	pass	pass	pass	fail	pass
		K17	pass	pass	pass	pass	pass
-40	3	HZLT4K26	pass	pass	pass	pass	pass
		K27	pass	pass	pass	pass	pass

* No data available on final crack size of specimens WMRTK11 and HZRTK21 because of ductile instability after extensive tearing (attempt to derive R curve for large crack growth)

Table 39. Assessment of crack qualification for weld metal centerline – dual torch (round 2)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	WMRTF02	fail	pass	pass	pass	pass
		F09	pass	pass	pass	pass	pass
	6	WMRTF04	pass	fail	pass	pass	pass
		F11	pass	pass	pass	pass	pass
-20	3	WMLTF10	fail	pass	pass	pass	fail
		F102	fail	pass	pass	pass	fail
	6	WMLTF03	pass	pass	pass	pass	pass
		F12	pass	pass	pass	fail	pass

Table 40. Assessment of crack qualification for HAZ [dual torch (round 2)], based on crack measurements on the weld metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	HZRTF05	pass	pass	pass	fail	pass
		F14	pass	pass	pass	fail	pass
	6	HZRTF07	pass	pass	pass	pass	pass
		F16	pass	pass	pass	fail	pass
-20	3	HZLTF06	pass	fail	pass	fail	pass
		F13	pass	pass	pass	fail	pass
	6	HZLTF08	pass	fail	pass	pass	pass
		F28	pass	pass	pass	fail	pass

* No data available on final crack size of specimens WMRTK11 and HZRTK21 because of ductile instability after extensive tearing (attempt to derive R curve for large crack growth)

Table 41. Assessment of crack qualification for HAZ [dual torch (round 2)], based on measurements on the base metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	HZRTF05	pass	pass	pass	pass	pass
		F14	pass	fail	pass	pass	pass
	6	HZRTF07	pass	fail	pass	fail	pass
		F16	pass	pass	pass	pass	pass
-20	3	HZLTF06	pass	fail	pass	pass	fail
		F13	pass	pass	pass	pass	pass
	6	HZLTF08	pass	fail	pass	pass	pass
		F28	pass	pass	pass	pass	pass

Table 42. Assessment of crack qualification for weld metal centerline - single torch (round 3)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DW1-B	fail	fail	pass	fail	fail
		DW3-A	pass	fail	pass	fail	pass
		DW6-A	pass	fail	pass	fail	pass
		FW1-A	pass	fail	pass	fail	pass
		FW3-A	fail	fail	pass	fail	fail
		FW6-A	pass	pass	pass	fail	pass

Table 43. Assessment of crack qualification for HAZ [single torch (round 3)], based on measurements on the weld metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DH1-A	pass	fail	fail	fail	pass
		DH3-A	pass	fail	pass	fail	pass
		DH6-A	pass	fail	fail	fail	pass
		FH1-A	pass	fail	fail	fail	pass
		FH3-A	pass	fail	pass	fail	pass
		FH6-A	fail	fail	fail	fail	fail

Table 44. Assessment of crack qualification for HAZ [single torch (round 3)], based on measurements on the base metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DH1-A	pass	fail	Fail	fail	pass
		DH3-A	pass	fail	Pass	fail	pass
		DH6-A	pass	fail	Fail	fail	pass
		FH1-A	pass	fail	Pass	fail	pass
		FH3-A	pass	fail	Pass	fail	pass
		FH6-A	pass	fail	Pass	fail	fail

5.2.2 SE(B)

Table 45. Assessment of crack qualification for base metal

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	6	BBMRT1	pass	pass	Pass	pass	pass
		T2	pass	pass	Pass	pass	pass
-20	3	BM2	pass	pass	Pass	pass	pass
		BM3	pass	fail	Pass	fail	pass
		BM4	pass	pass	Pass	pass	pass
		BM5	pass	pass	Pass	fail	fail
		BM6	pass	pass	Pass	fail	pass

Table 46. Assessment of crack qualification for weld metal centerline - single torch (round 1)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	BWMRTG05	pass	pass	pass	pass	pass
		I10	fail	pass	pass	pass	fail
	6	BWMRTI04	fail	pass	pass	pass	pass
		I11	fail	pass	pass	pass	pass
-20	3	BWMLTI01	fail	pass	pass	pass	pass
		I02	fail	pass	pass	pass	fail
	6	BWMLTG06	fail	pass	pass	pass	pass
		I12	pass	pass	pass	pass	pass

Table 47. Assessment of crack qualification for HAZ [single torch (round 1)], based on crack measurements on the weld metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	BHZRTI05	pass	pass	pass	pass	pass
		I06	pass	pass	pass	pass	pass
	6	BHZRTG04	pass	pass	pass	pass	pass
		I08	pass	pass	pass	fail	pass
-20	3	I14	pass	pass	pass	fail	pass
	6	BHZLTG08	pass	pass	pass	pass	pass
		I15	pass	pass	pass	pass	pass

Table 48. Assessment of crack qualification for HAZ [single torch (round 1)], based on measurements on the base metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	BHZRTI05	pass	pass	pass	pass	pass
		I06	pass	pass	pass	pass	pass
	6	BHZRTG04	pass	pass	pass	pass	pass
		I08	pass	pass	pass	pass	pass
-20	3	I14	pass	pass	pass	pass	pass
	6	BHZLTG08	pass	pass	pass	fail	pass
		I15	pass	pass	pass	pass	pass

Table 49. Assessment of crack qualification for weld metal centerline - dual torch (round 2)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
RT	3	BWMRTF21	fail	pass	pass	pass	pass
	6	BWMRTF23	pass	pass	pass	pass	pass
-20	3	BWMLTF22	fail	pass	pass	pass	pass
	6	BWMLTF24	pass	pass	pass	pass	pass

Table 50. Assessment of crack qualification for weld metal centerline - single torch (round 3)

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DW1	pass	fail	pass	pass	pass
		DW3	pass	fail	pass	pass	pass
		DW6	pass	fail	pass	fail	pass
		FW1	pass	fail	pass	fail	pass
		FW3	pass	fail	pass	pass	fail
		FW6	pass	fail	pass	pass	fail

Table 51. Assessment of crack qualification for HAZ [single torch (round 3)], based on measurements on the base metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DH1	pass	pass	Pass	pass	pass
		DH6	pass	pass	Pass	fail	pass
		FH1	pass	pass	Fail	fail	pass
		FH3	pass	pass	Pass	pass	pass
		FH6	pass	pass	Pass	pass	pass

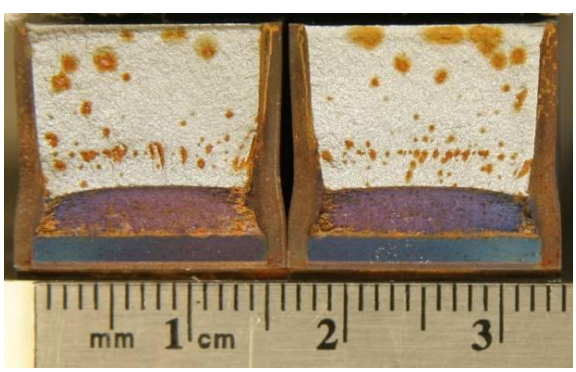
Table 52. Assessment of crack qualification for HAZ [single torch (round 3)], based on measurements on the weld metal side

Temp (°C)	Target a_o (mm)	ID	ASTM E1820				BS 7448: Part 2
			9.1.4.1	9.1.4.2	9.1.5.1	9.1.5.2	12.4.1
-20	3	DH1	pass	pass	pass	pass	pass
		DH6	pass	pass	pass	fail	pass
		FH1	pass	pass	pass	fail	pass
		FH3	pass	fail	fail	pass	pass
		FH6	pass	fail	pass	pass	pass

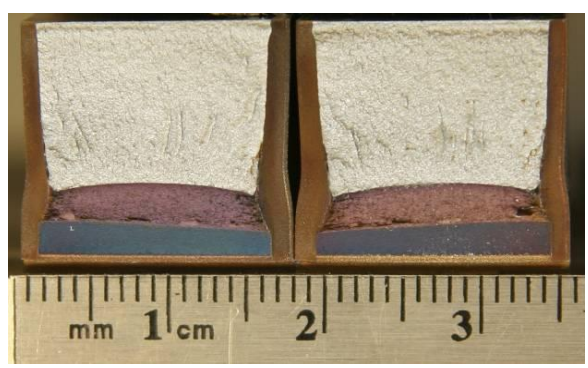
5.3 Fracture Surfaces

This section contains photographs of fracture surfaces of all tested SE(T) and SE(B) specimens broken after testing for crack length measurements and evaluation of crack front straightness.

5.3.1 SE(T)

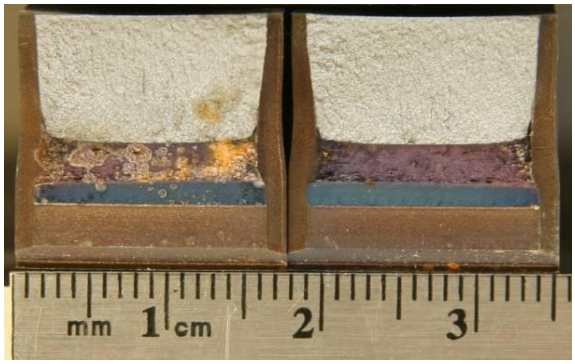


(a) RT, a = 3 mm (BMRTK06)

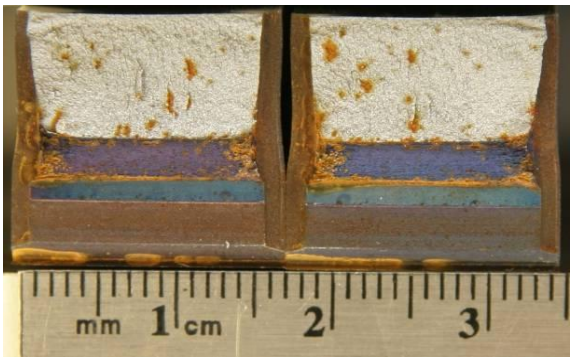


(b) RT, a = 3 mm (BMRTK09)

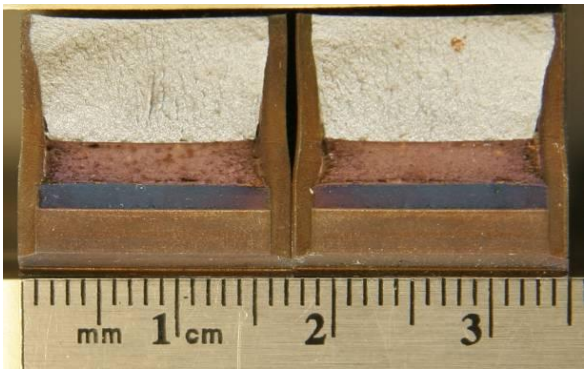
Figure 30 continued on next page below



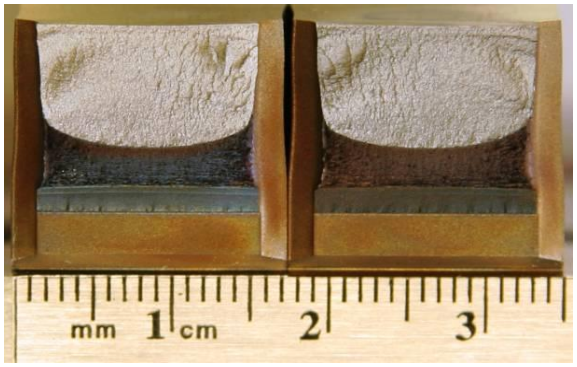
(c) RT, a = 6 mm (BMRTK12)



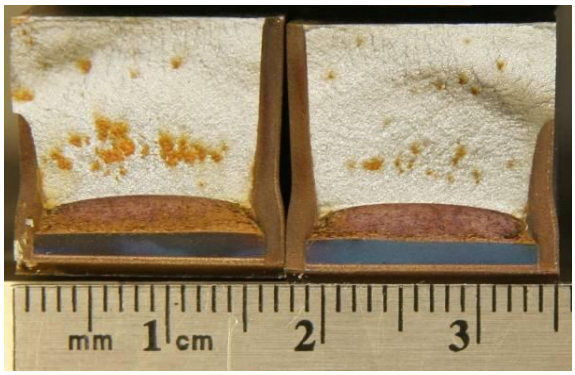
(d) RT, *a* = 6 mm(K13)



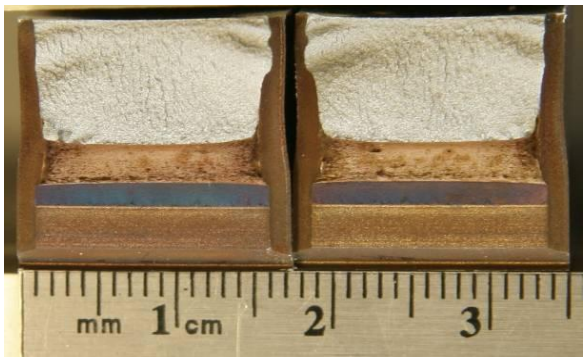
(e) RT, *a* = 6 mm (K14)



(f) RT, *a* = 6 mm (K02)

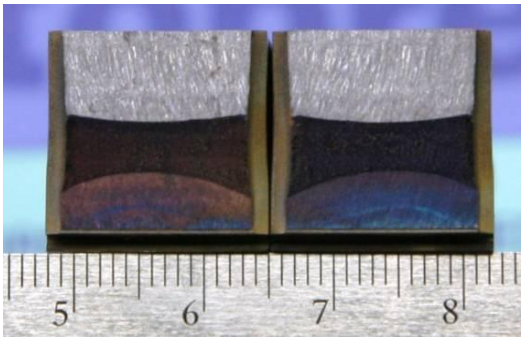


(e) -20 ˚C, *a* = 3 mm (BMLTK10)

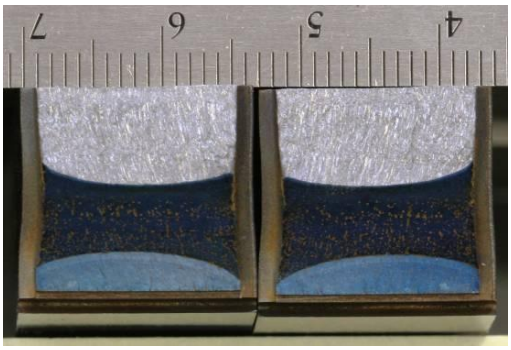


(f) -20 ˚C, *a* = 6 mm (BMLTK11)

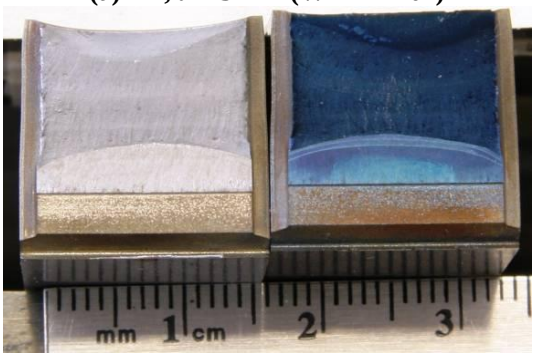
Figure 30. Fracture surfaces of SE(T) base metal specimens



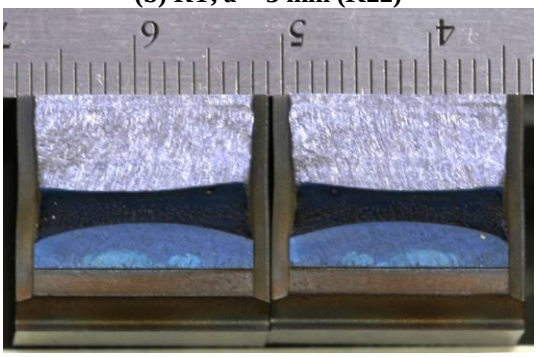
(a) RT, *a* = 3 mm (WMRTK01)



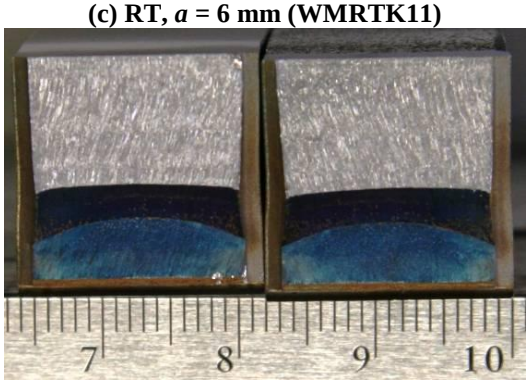
(b) RT, *a* = 3 mm (K22)



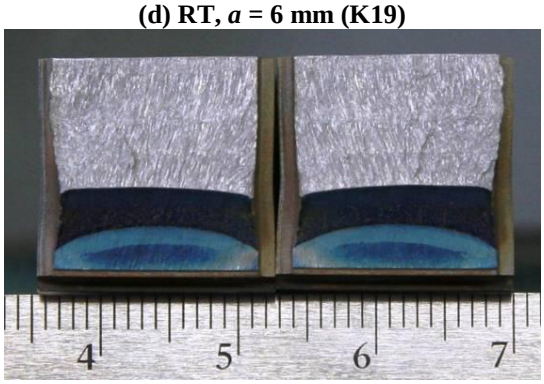
(c) RT, *a* = 6 mm (WMRTK11)



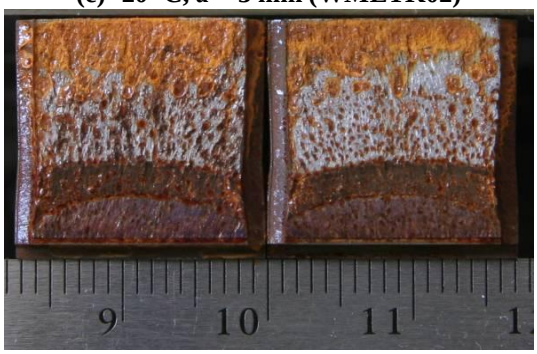
(d) RT, *a* = 6 mm (K19)



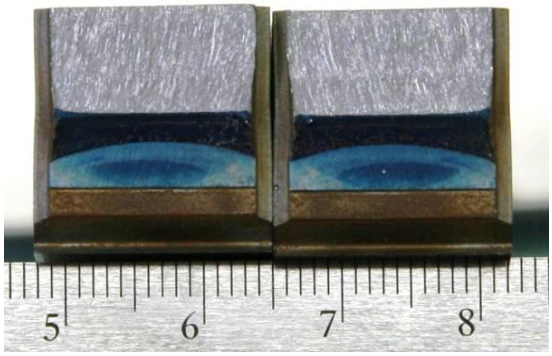
(e) -20 ˚C, *a* = 3 mm (WMLTK02)



(f) -20 ˚C, *a* = 3 mm (K15)

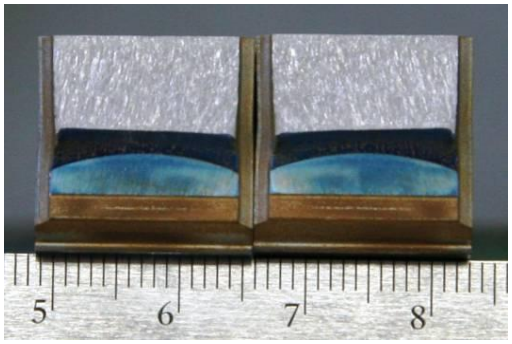


(g) -20 ˚C, *a* = 3 mm (K23)

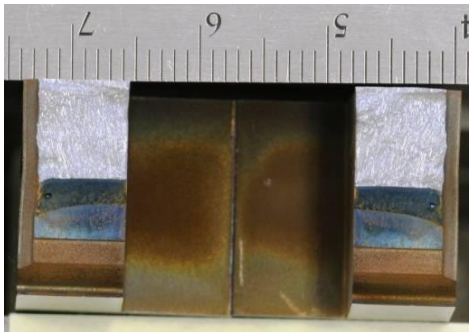


(h) -20 ˚C, *a* = 6 mm (WMLTK12)

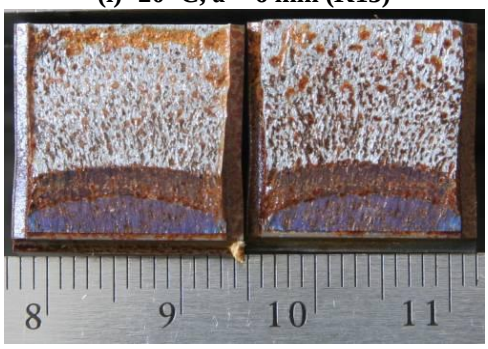
Figure 31 continued on next page below



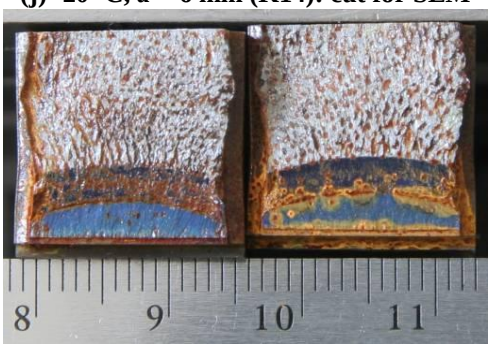
(i) -20 ˚C, *a* = 6 mm (K13)



(j) -20 ˚C, *a* = 6 mm (K14): cut for SEM

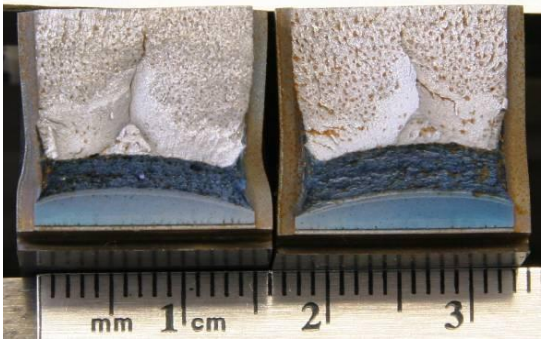


(k) -40 ˚C, *a* = 3 mm (WMLT4K24)

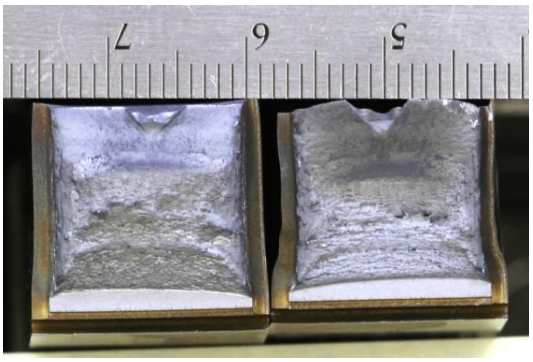


(l) -40 ˚C, *a* = 6 mm (K25)

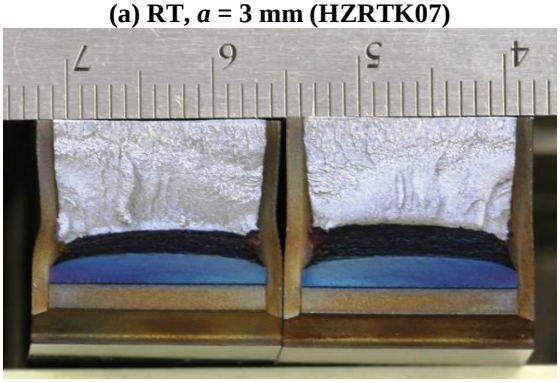
Figure 31. Fracture surfaces of SE(T) single torch weld metal (round 1)



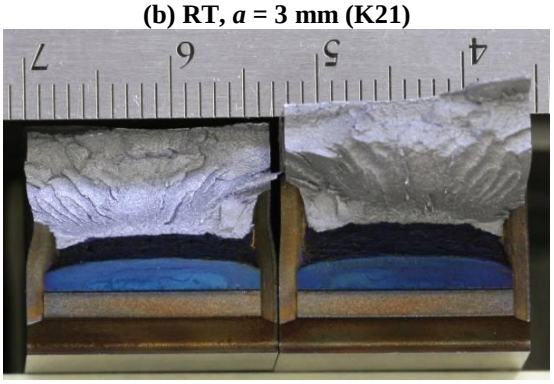
(a) RT, *a* = 3 mm (HZRTK07)



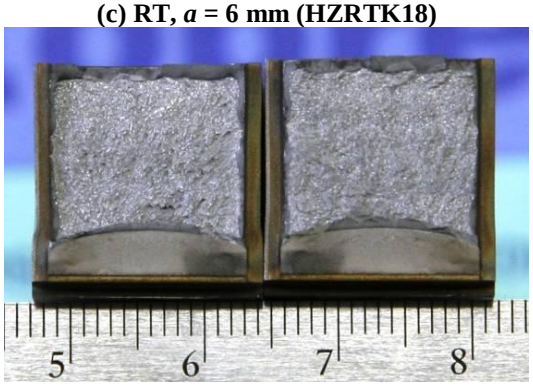
(b) RT, *a* = 3 mm (K21)



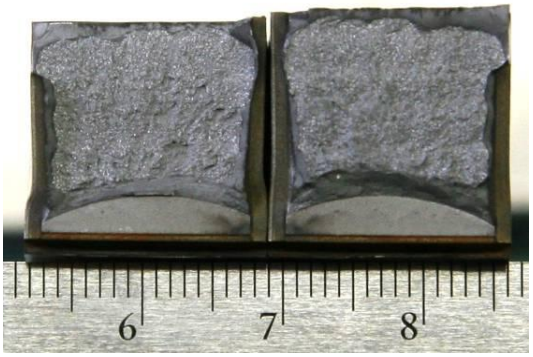
(c) RT, *a* = 6 mm (HZRTK18)



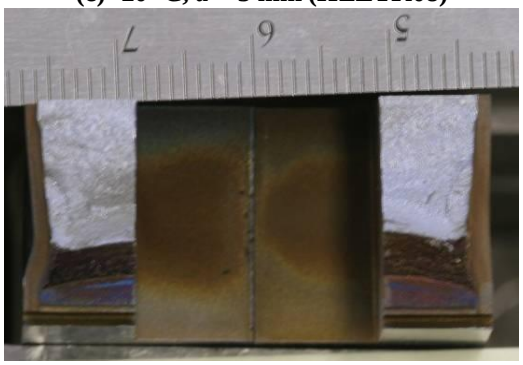
(d) RT, *a* = 6 mm (K20)



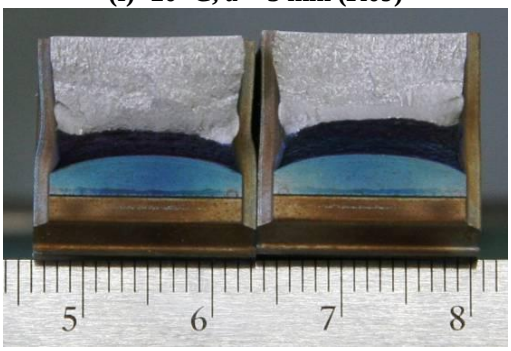
(e) -20 ˚C, *a* = 3 mm (HZLTK08)



(f) -20 ˚C, *a* = 3 mm (K09)

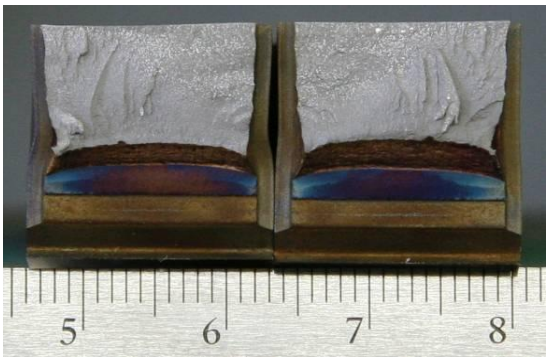


(g) -20 ˚C, *a* = 3 mm (K16): cut for SEM

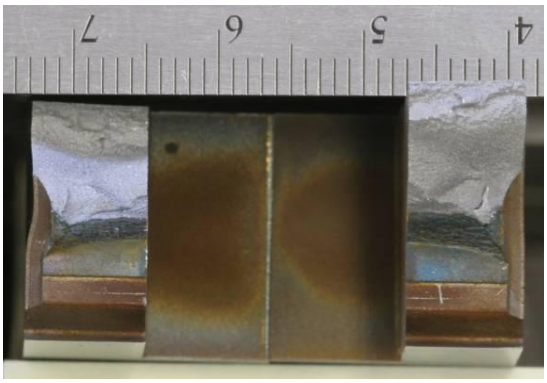


(h) -20 ˚C, *a* = 6 mm (HZLTK05)

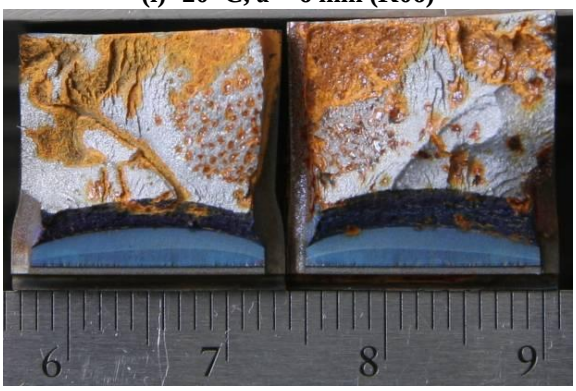
Figure 32 continued on next page below



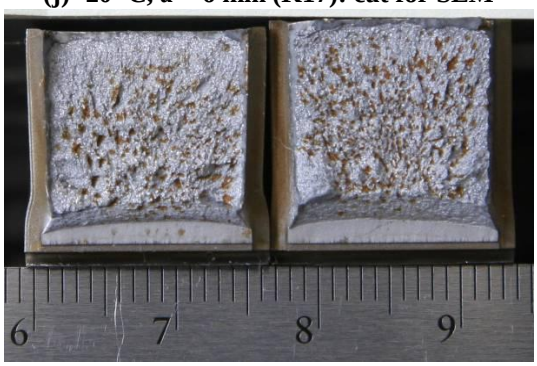
(i) -20 ˚C, *a* = 6 mm (K06)



(j) -20 ˚C, *a* = 6 mm (K17): cut for SEM

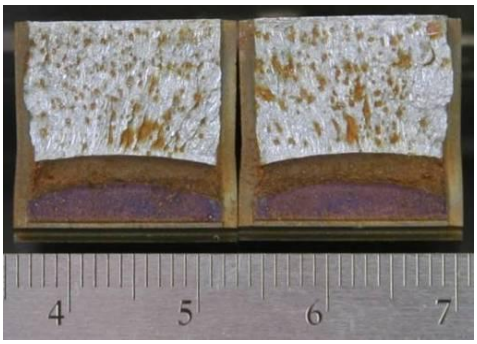


(k) -40 ˚C, *a* = 3 mm (HZLT4K26)

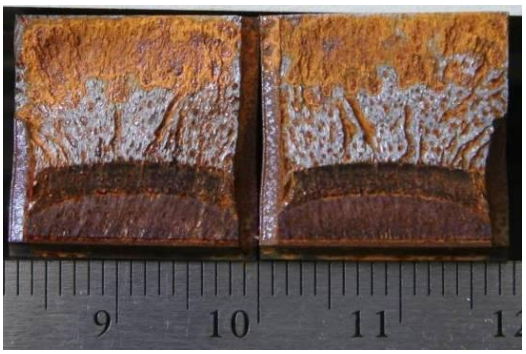


(l) -40 ˚C, *a* = 6 mm (K27): cut for SEM

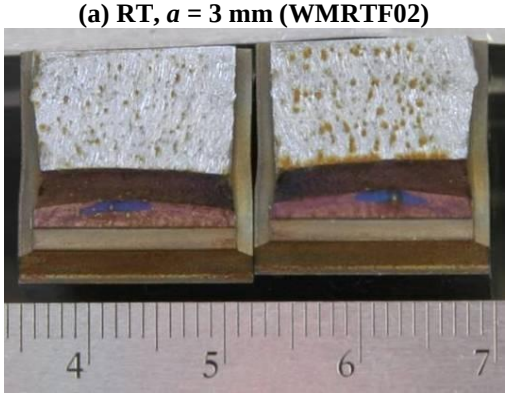
Figure 32. Fracture surfaces of SE(T) single torch HAZ (round 1)



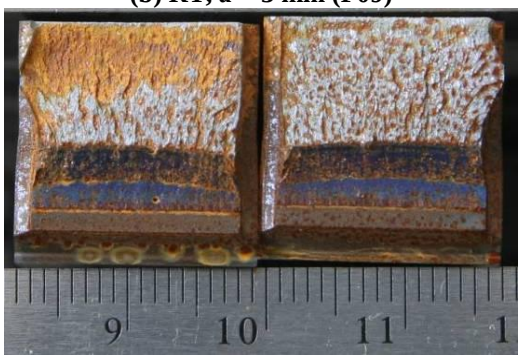
(a) RT, *a* = 3 mm (WMRTF02)



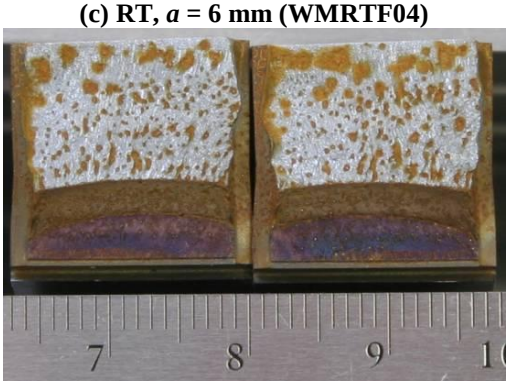
(b) RT, *a* = 3 mm (F09)



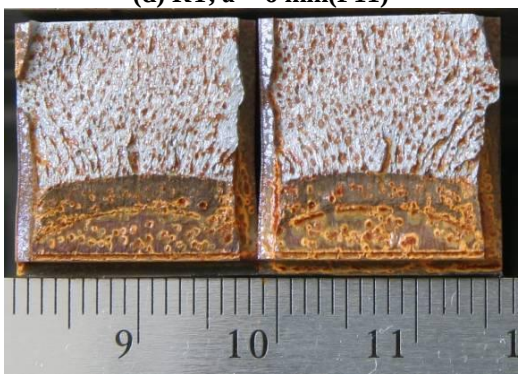
(c) RT, *a* = 6 mm (WMRTF04)



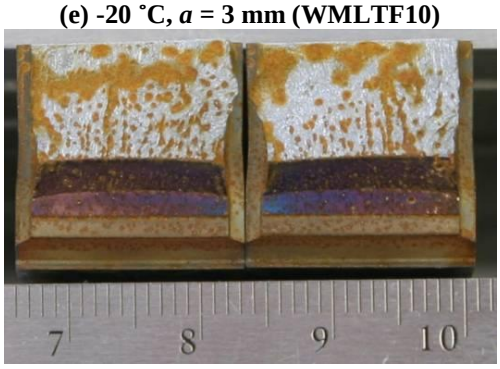
(d) RT, *a* = 6 mm(F11)



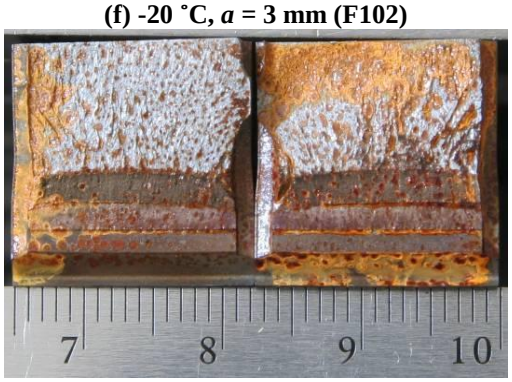
(e) -20 ˚C, *a* = 3 mm (WMLTF10)



(f) -20 ˚C, *a* = 3 mm (F102)

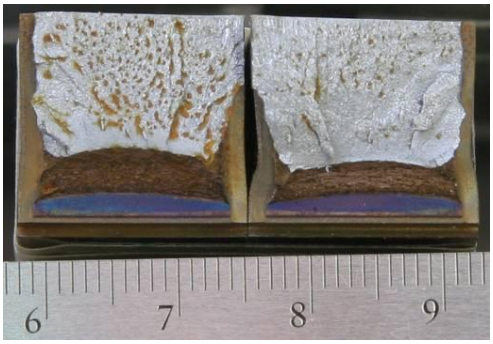


(g) -20 ˚C, *a* = 6 mm (WMLTF03)

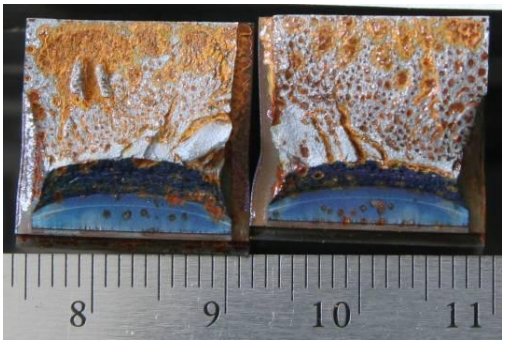


(h) -20 ˚C, *a* = 6 mm (F12)

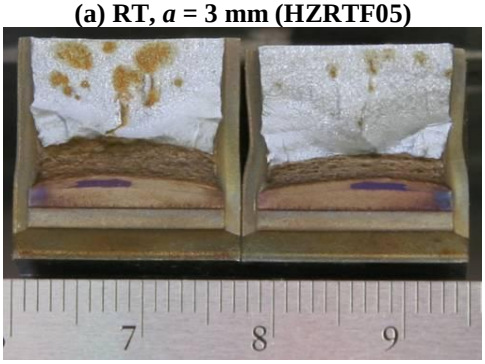
Figure 33. Fracture surfaces of SE(T) dual torch weld metal (round 2)



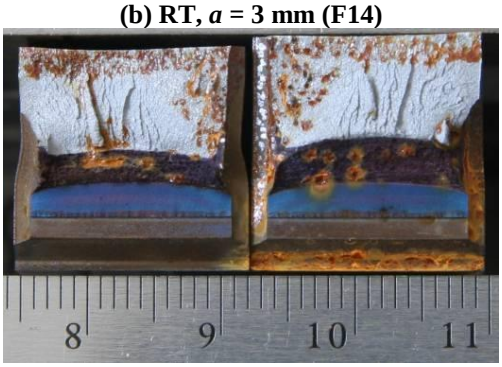
(a) RT, *a* = 3 mm (HZRTF05)



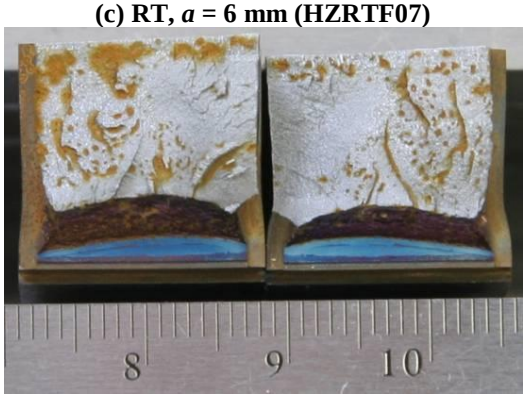
(b) RT, *a* = 3 mm (F14)



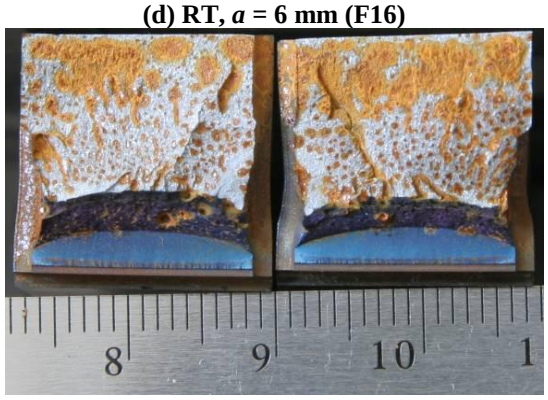
(c) RT, *a* = 6 mm (HZRTF07)



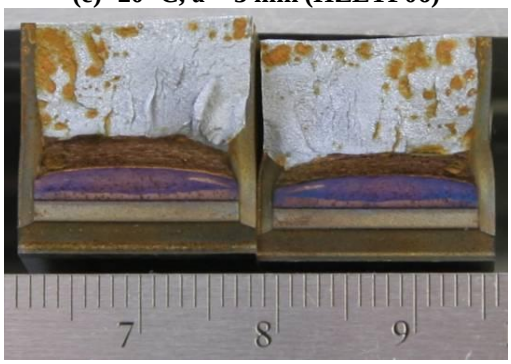
(d) RT, *a* = 6 mm (F16)



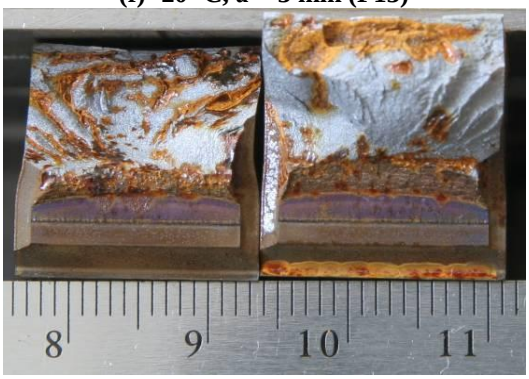
(e) -20 ˚C, *a* = 3 mm (HZLTF06)



(f) -20 ˚C, *a* = 3 mm (F13)

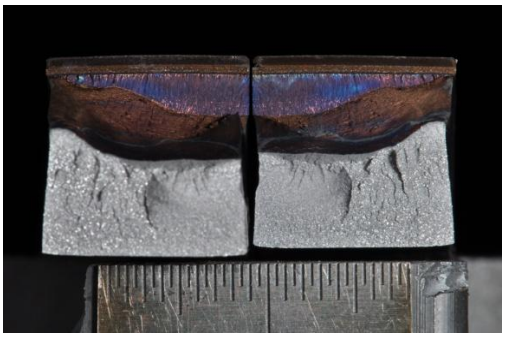


(g) -20 ˚C, *a* = 6 mm (HZLTF08)

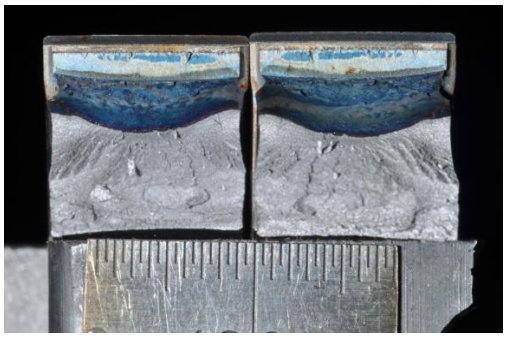


(h) -20 ˚C, *a* = 6 mm (F28)

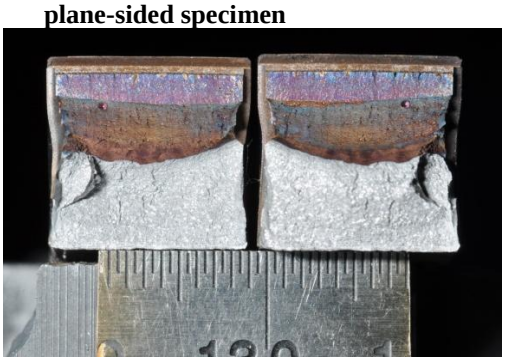
Figure 34. Fracture surfaces of SE(T) dual torch HAZ (round 2)



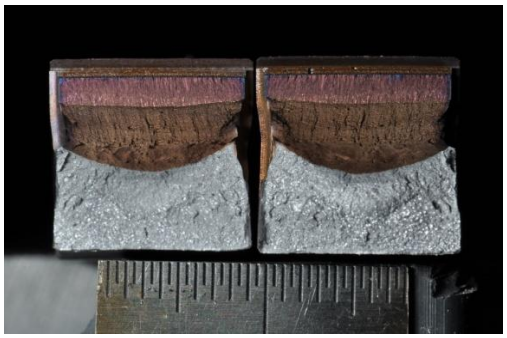
(a) -20 °C, *a* = 3mm (DW1-B); plane-sided specimen



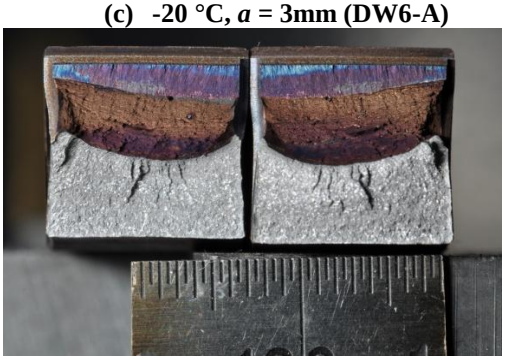
(b) -20 °C, *a* = 3mm (DW3-A)



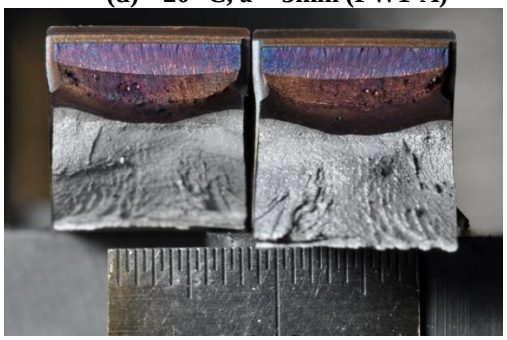
(c) -20 °C, *a* = 3mm (DW6-A)



(d) -20 °C, *a* = 3mm (FW1-A)

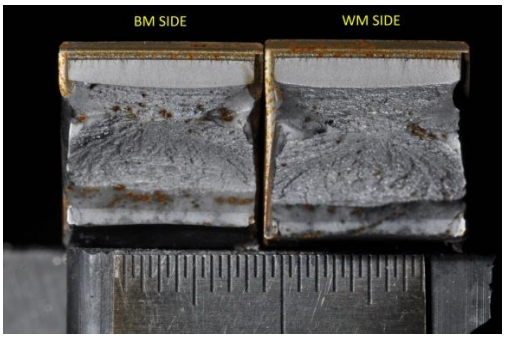


(e) -20 °C, *a* = 3mm (FW3-A)

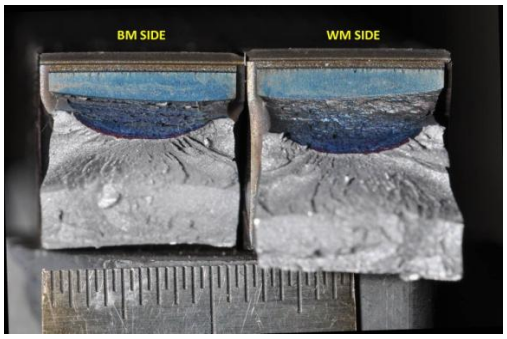


(f) -20 °C, *a* = 3mm (FW6-A)

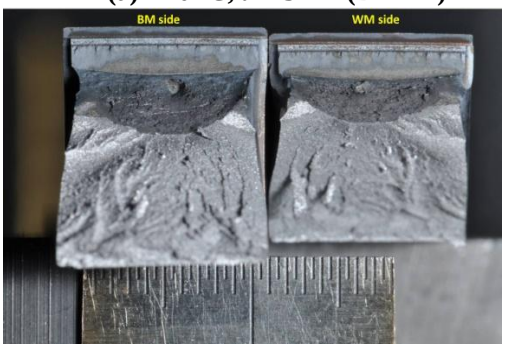
Figure 35. Fracture surfaces of SE(T) single torch weld metal (round 3)



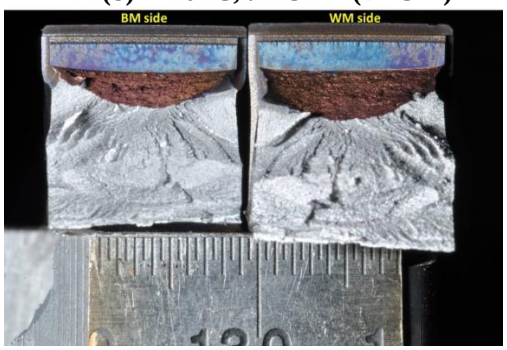
(a) -20 °C, *a* = 3mm (DH1-A)



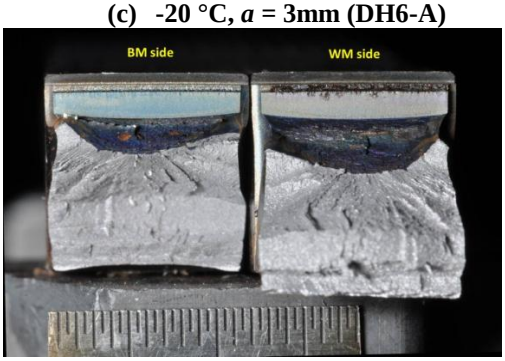
(b) – 20 °C, *a* = 3mm (DH3-A)



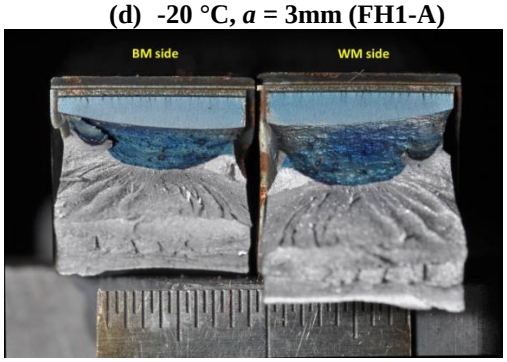
(c) -20 °C, *a* = 3mm (DH6-A)



(d) -20 °C, *a* = 3mm (FH1-A)



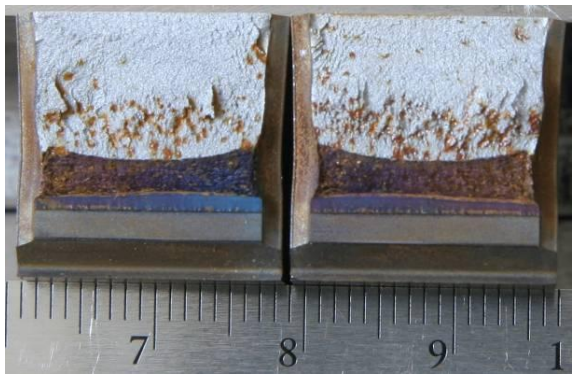
(e) -20 °C, *a* = 3mm (FH3-A)



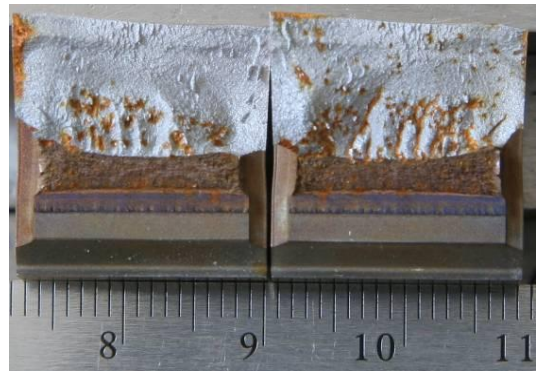
(f) -20 °C, *a* = 3mm (FH6-A)

Figure 36. Fracture surfaces of SE(T) single torch HAZ (round 3)

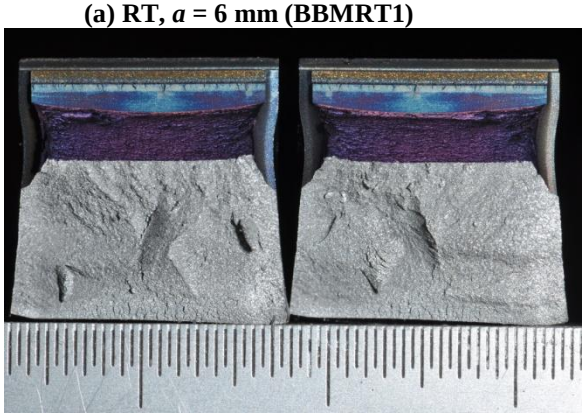
5.3.2 SE(B)



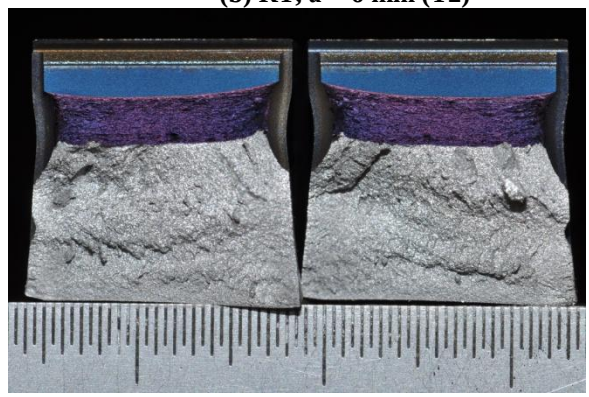
(a) RT, *a* = 6 mm (BBMRT1)



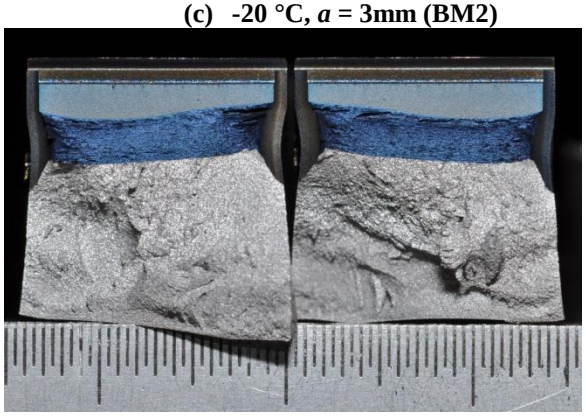
(b) RT, *a* = 6 mm (T2)



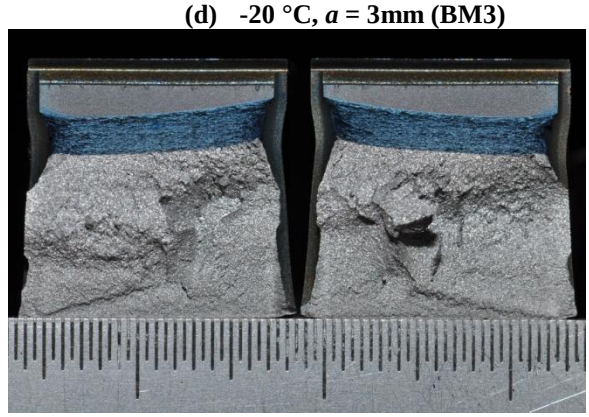
(c) -20 °C, *a* = 3mm (BM2)



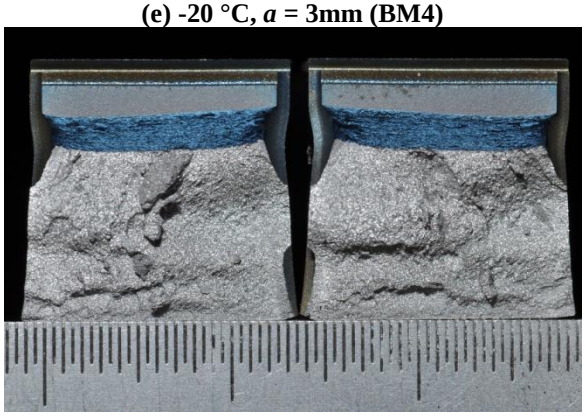
(d) -20 °C, *a* = 3mm (BM3)



(e) -20 °C, *a* = 3mm (BM4)

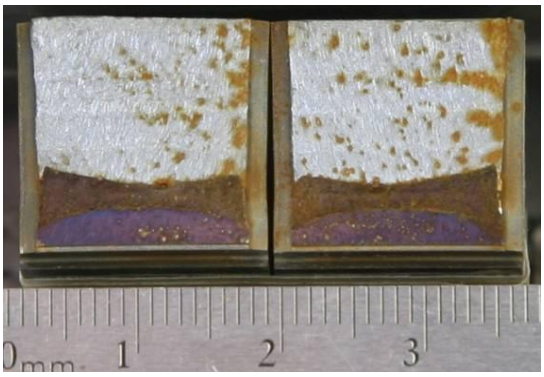


(f) -20 °C, *a* = 3mm (BM5)

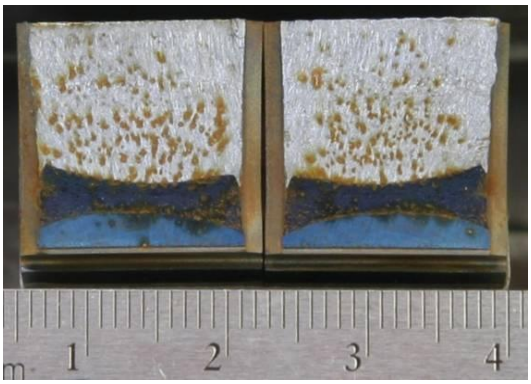


(g) -20 °C, *a* = 3mm (BM6)

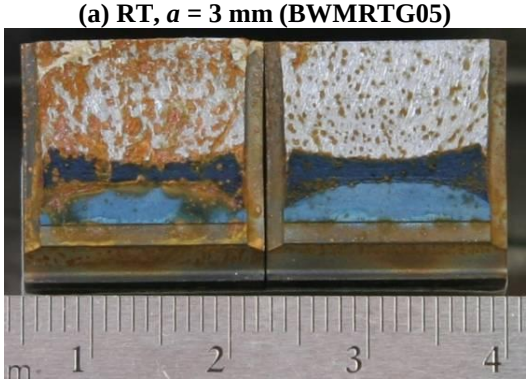
Figure 37. Fracture surfaces of SE(B) base metal specimens



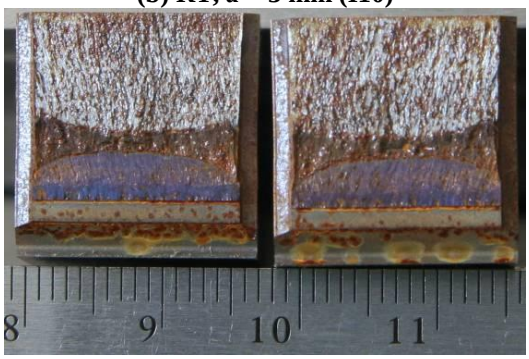
(a) RT, *a* = 3 mm (BWMRTG05)



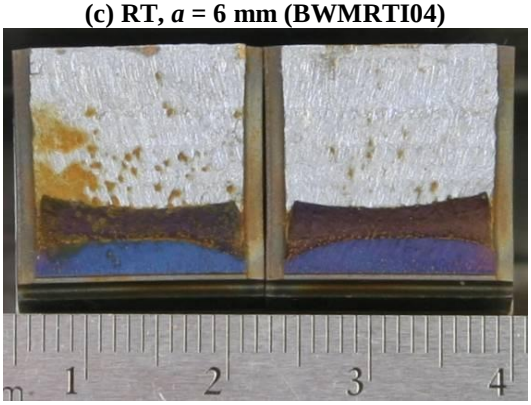
(b) RT, *a* = 3 mm (I10)



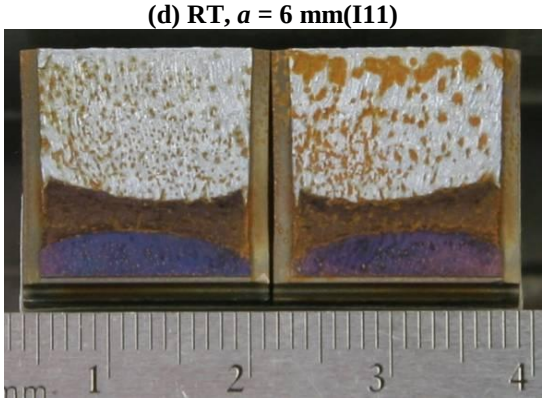
(c) RT, *a* = 6 mm (BWMRTI04)



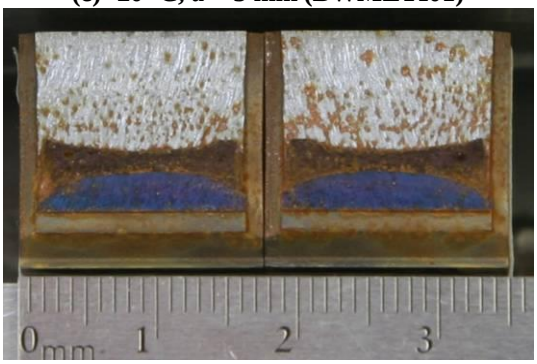
(d) RT, *a* = 6 mm(I11)



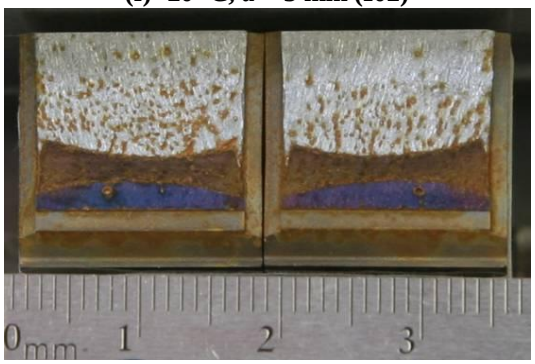
(e) -20 ˚C, *a* = 3 mm (BWMLTI01)



(f) -20 ˚C, *a* = 3 mm (I02)

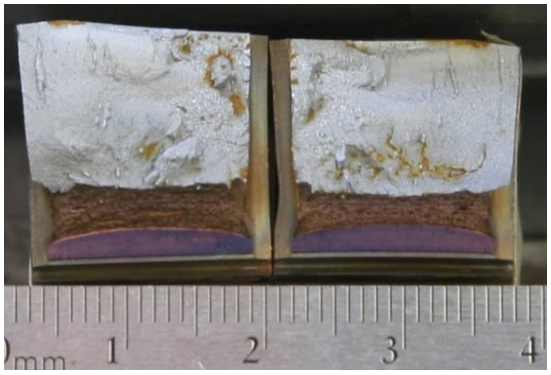


(g) -20 ˚C, *a* = 6 mm (BWMLTG06)

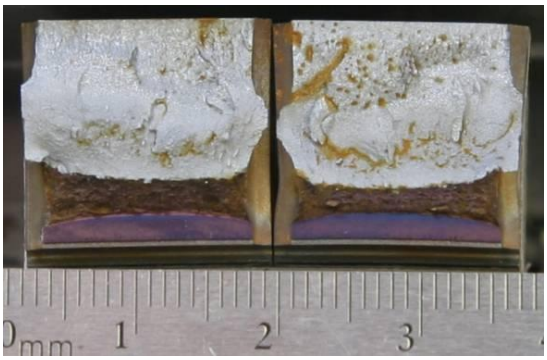


(h) -20 ˚C, *a* = 6 mm (I12)

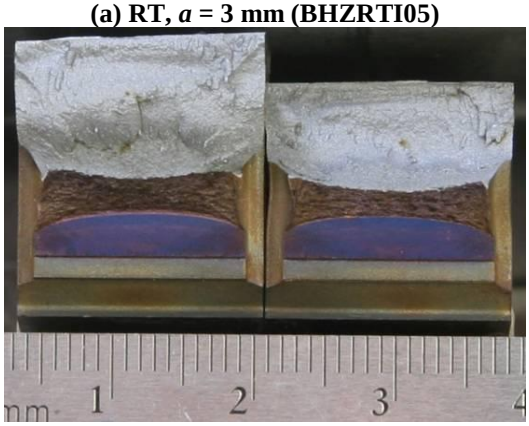
Figure 38. Fracture surfaces of SE(B) single torch weld metal (round 1)



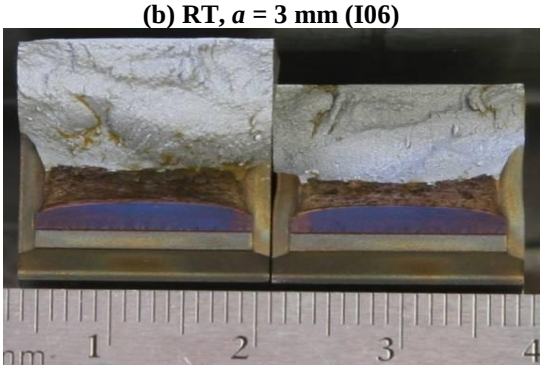
(a) RT, *a* = 3 mm (BHZRTI05)



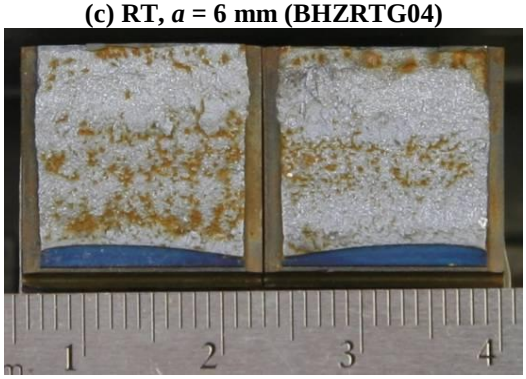
(b) RT, *a* = 3 mm (I06)



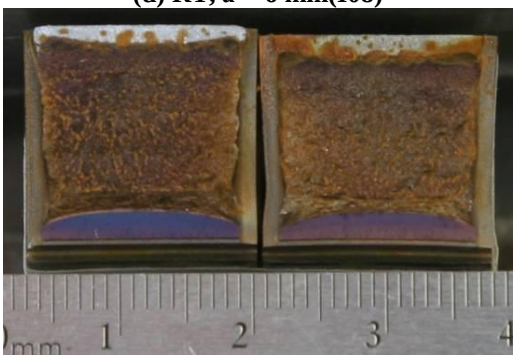
(c) RT, *a* = 6 mm (BHZRTG04)



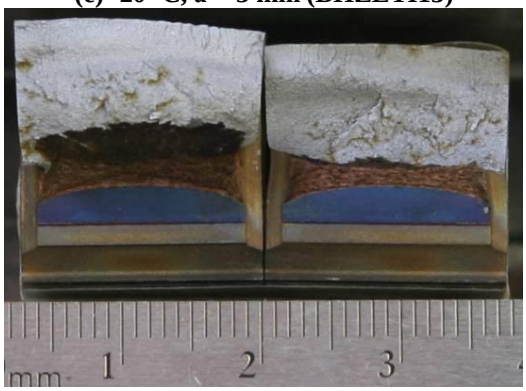
(d) RT, *a* = 6 mm(I08)



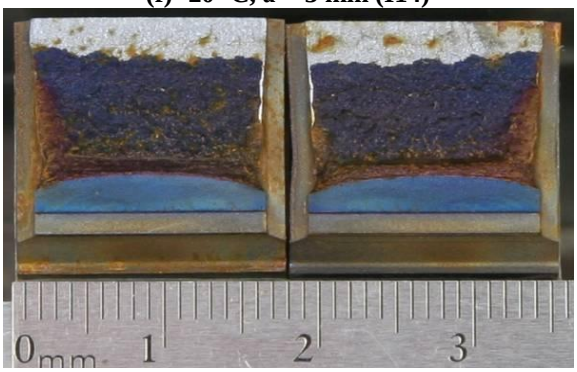
(e) -20 ˚C, *a* = 3 mm (BHZLTI13)



(f) -20 ˚C, *a* = 3 mm (I14)

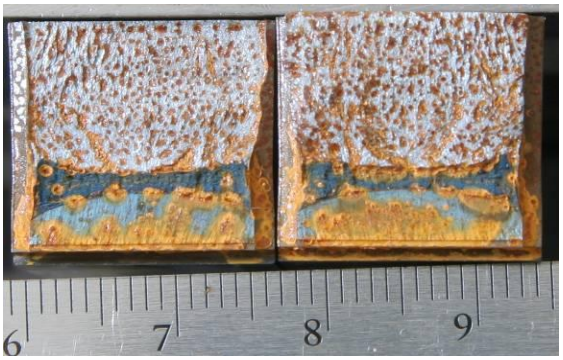


(g) -20 ˚C, *a* = 6 mm (BHZLTG08)

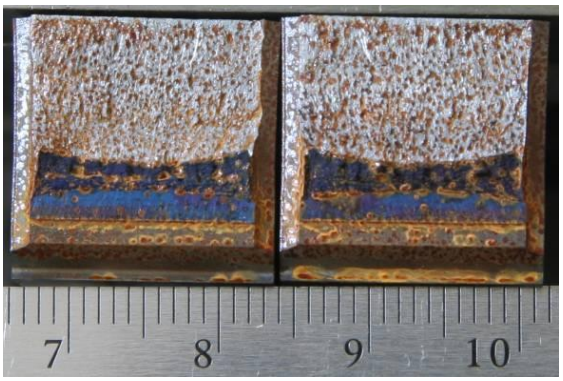


(h) -20 ˚C, *a* = 6 mm (I15)

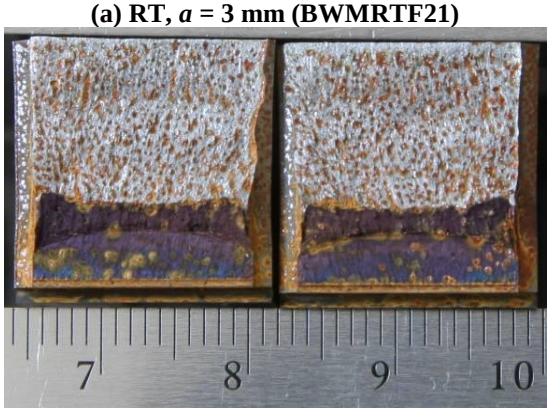
Figure 39. Fracture surfaces of SE(B) single torch HAZ (round 1)



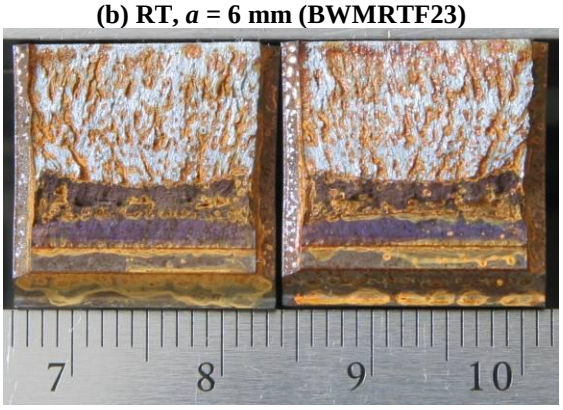
(a) RT, *a* = 3 mm (BWMRTF21)



(b) RT, *a* = 6 mm (BWMRTF23)

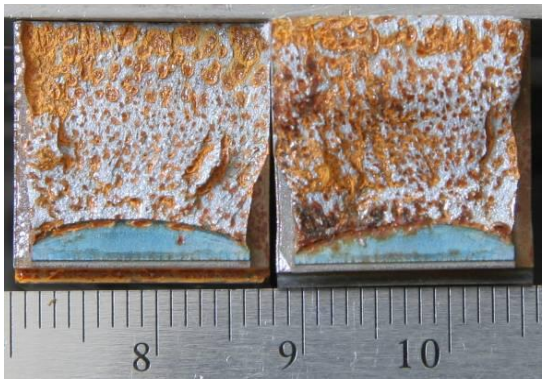


(c) -20 ˚C, *a* = 3 mm (BWMLTF22)

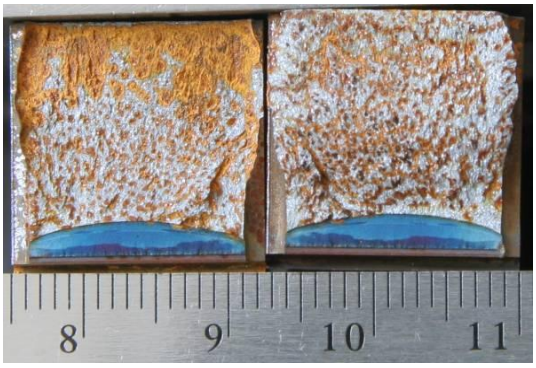


(d) -20 ˚C, *a* = 6 mm (BWMLTF24)

Figure 40. Fracture surfaces of SE(B) dual torch weld metal (round 2)

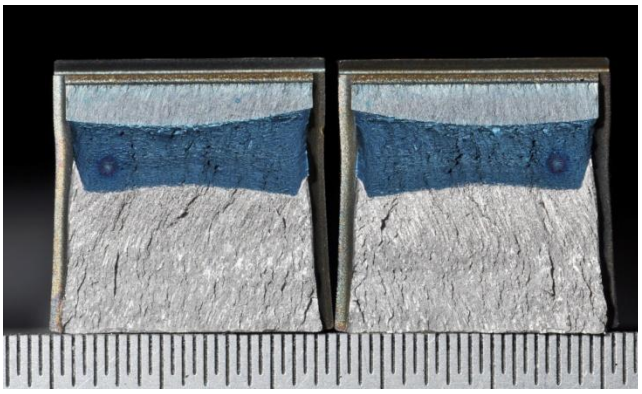


(a) RT, *a* = 3 mm (BHZLTF25)

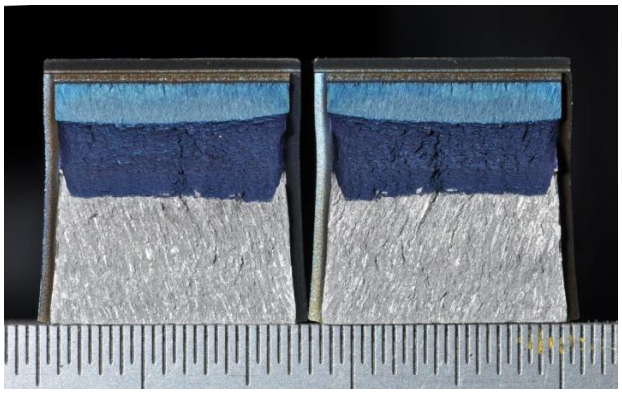


(b) -20 ˚C, *a* = 3 mm (BHZLTF26)

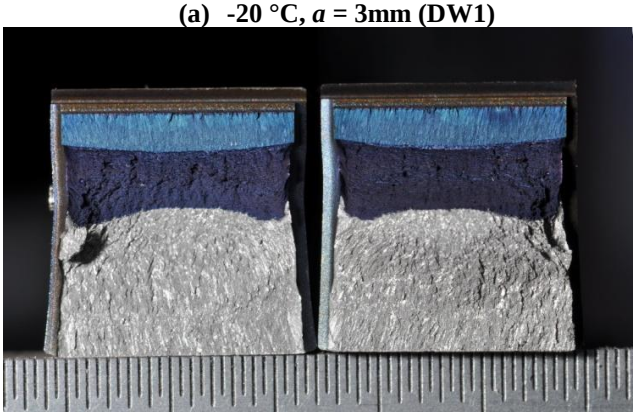
Figure 41. Fracture surfaces of SE(B) dual torch HAZ (round 2)



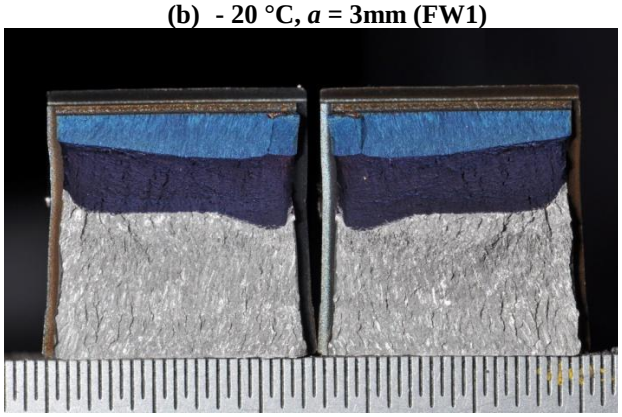
(a) -20 °C, *a* = 3mm (DW1)



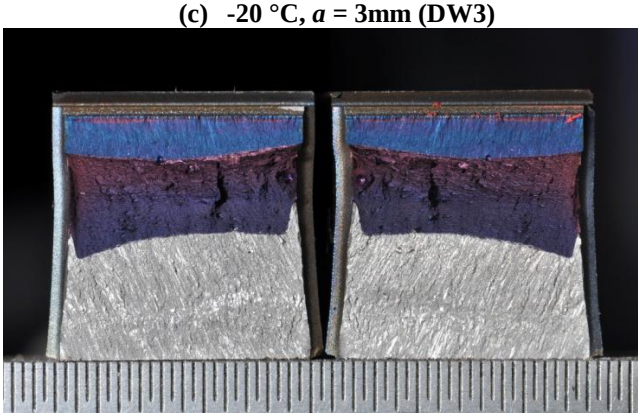
(b) - 20 °C, *a* = 3mm (FW1)



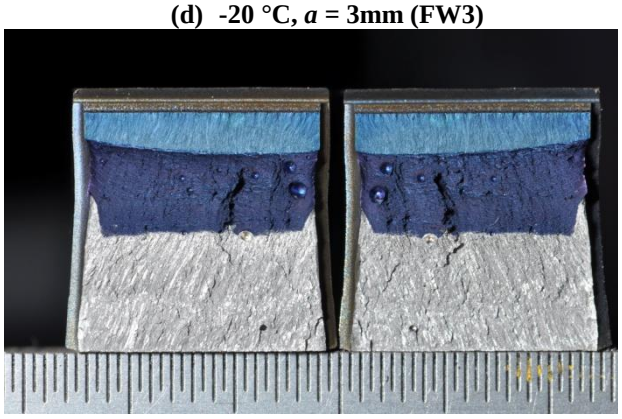
(c) -20 °C, *a* = 3mm (DW3)



(d) -20 °C, *a* = 3mm (FW3)

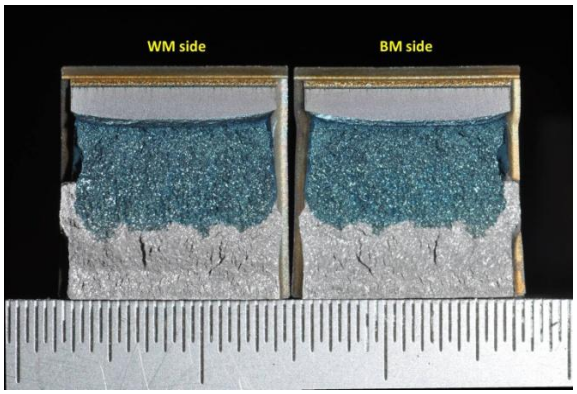


(e) -20 °C, *a* = 3mm (DW6)

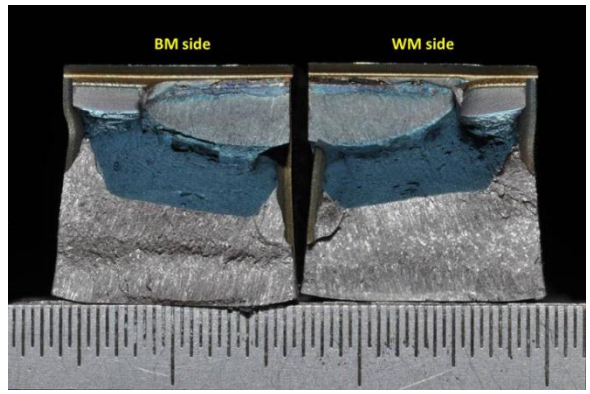


(f) -20 °C, *a* = 3mm (FW6)

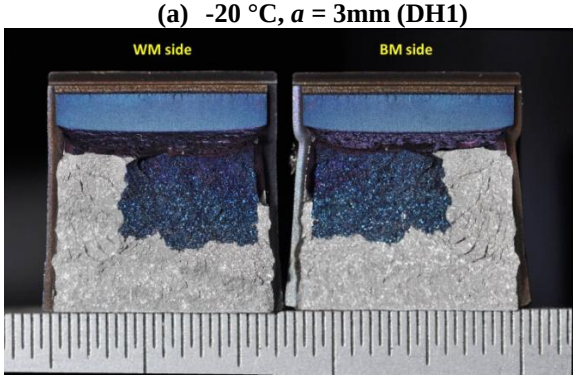
Figure 42. Fracture surfaces of SE(B) single torch weld metal (round 3)



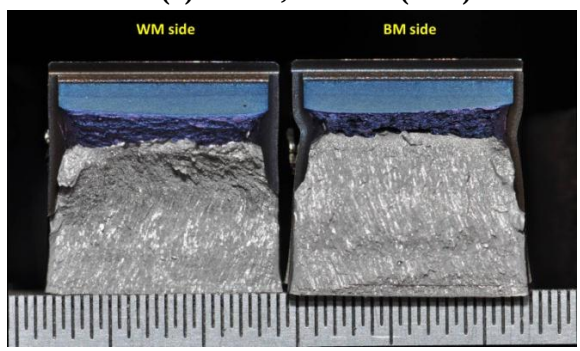
(a) -20 °C, *a* = 3mm (DH1)



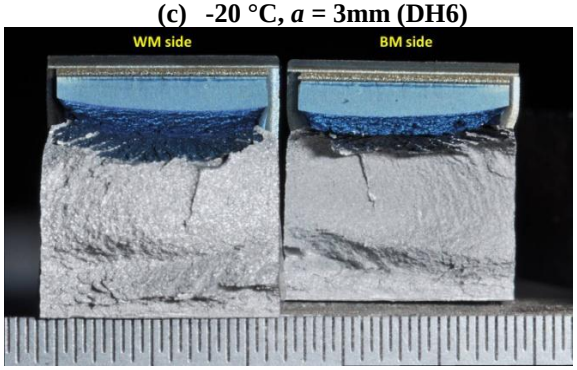
(b) -20 °C, *a* = 3mm (DH3)



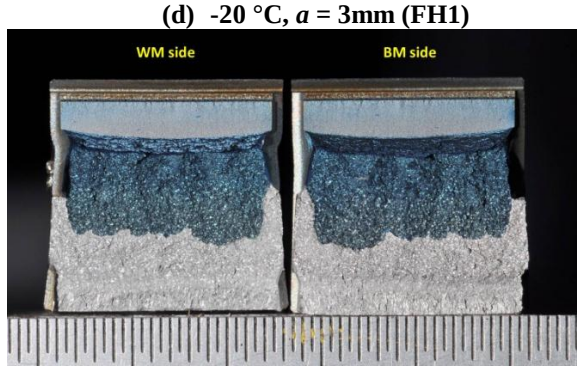
(c) -20 °C, *a* = 3mm (DH6)



(d) -20 °C, *a* = 3mm (FH1)



(e) -20 °C, *a* = 3mm (DH6)



(f) -20 °C, *a* = 3mm (FH6)

Figure 43. Fracture surfaces of SE(B) single torch HAZ (round 3)

6 ACKNOWLEDGMENTS

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