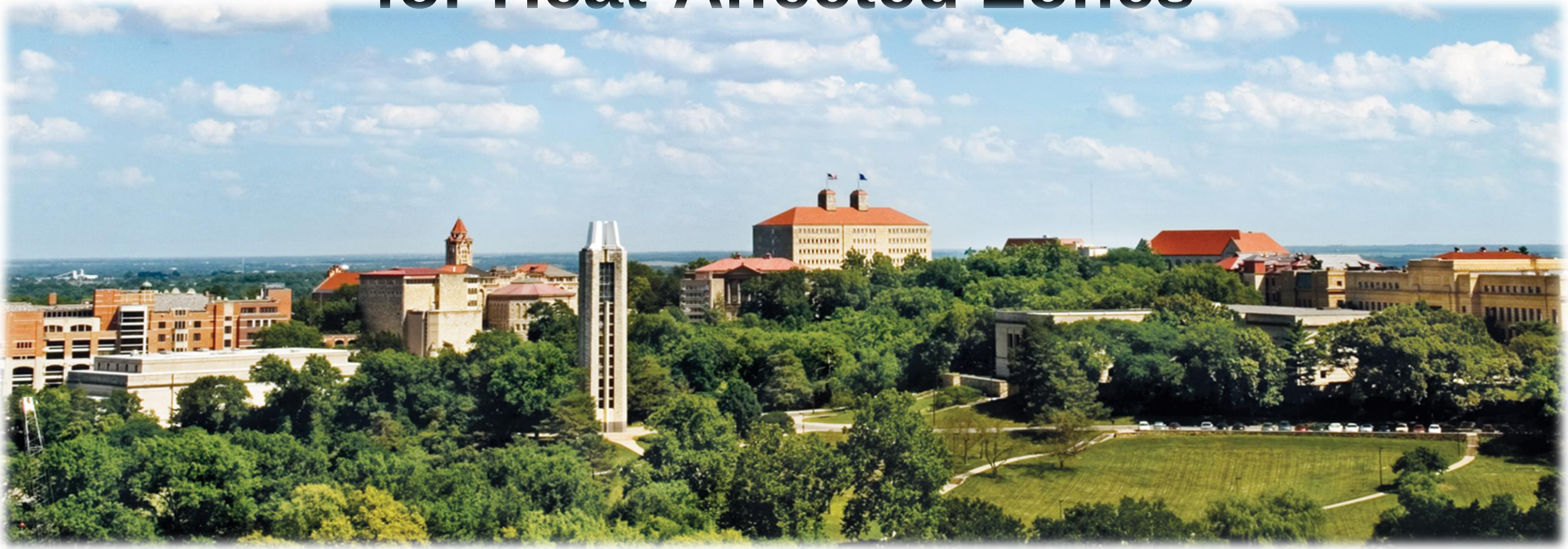
Fracture Toughness of Weldments for Heat-Affected Zones



William Collins

Acknowledgements

Students

Tristan Yount
Ryan Landreneau
Zahra Andalib

Collaborators

Rick Link
John Barsom
Karl Frank
Matthew Fadden
Stan Rolfe
Duane Miller
Mike Florczykowski

Background and Motivation

- Microstructural changes affect mechanical properties
  - Includes fracture toughness
- Welding temperatures induce changes in base metal
  - BM near weld interface- Heat-affected Zone (HAZ)
- Welding processes change HAZ fracture toughness
  - (Fairchild 1990, Wood 1986)
- Testing indicated low fracture toughness in HAZ
  - (Satoh 1988, Haze 1988, Webster 1988)

NCHRP 10-95A Overview

Literature Review

- Influencing Factors
- Data Mining

Pilot Study

- Heat Input Normalization
- Best Practices

Full Fracture Characterization Study

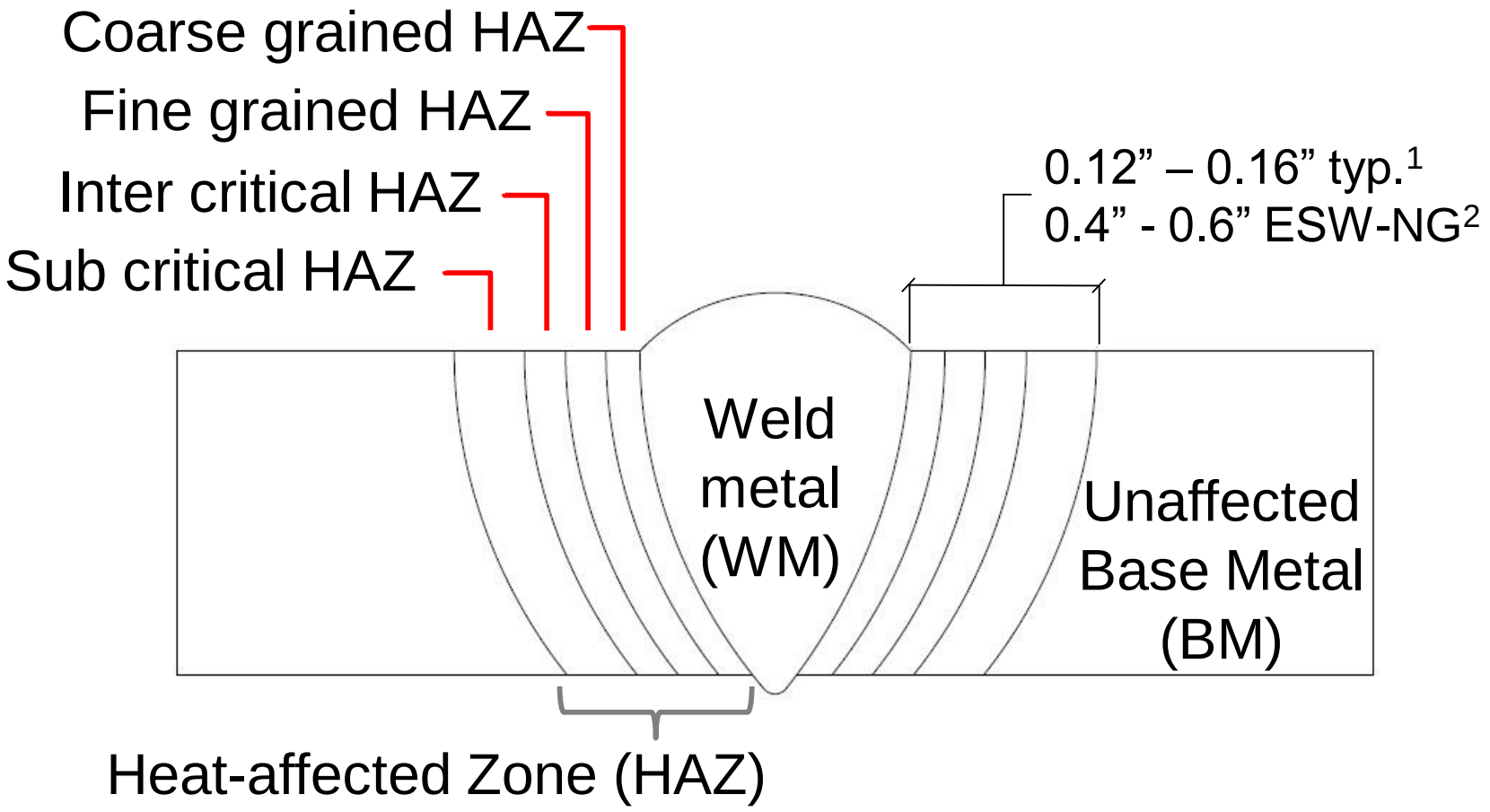
- CVN Impact Energy
- Fracture Toughness Testing

Analysis

- Comparison with Current Requirements
- Critical Flaw Size Analyses

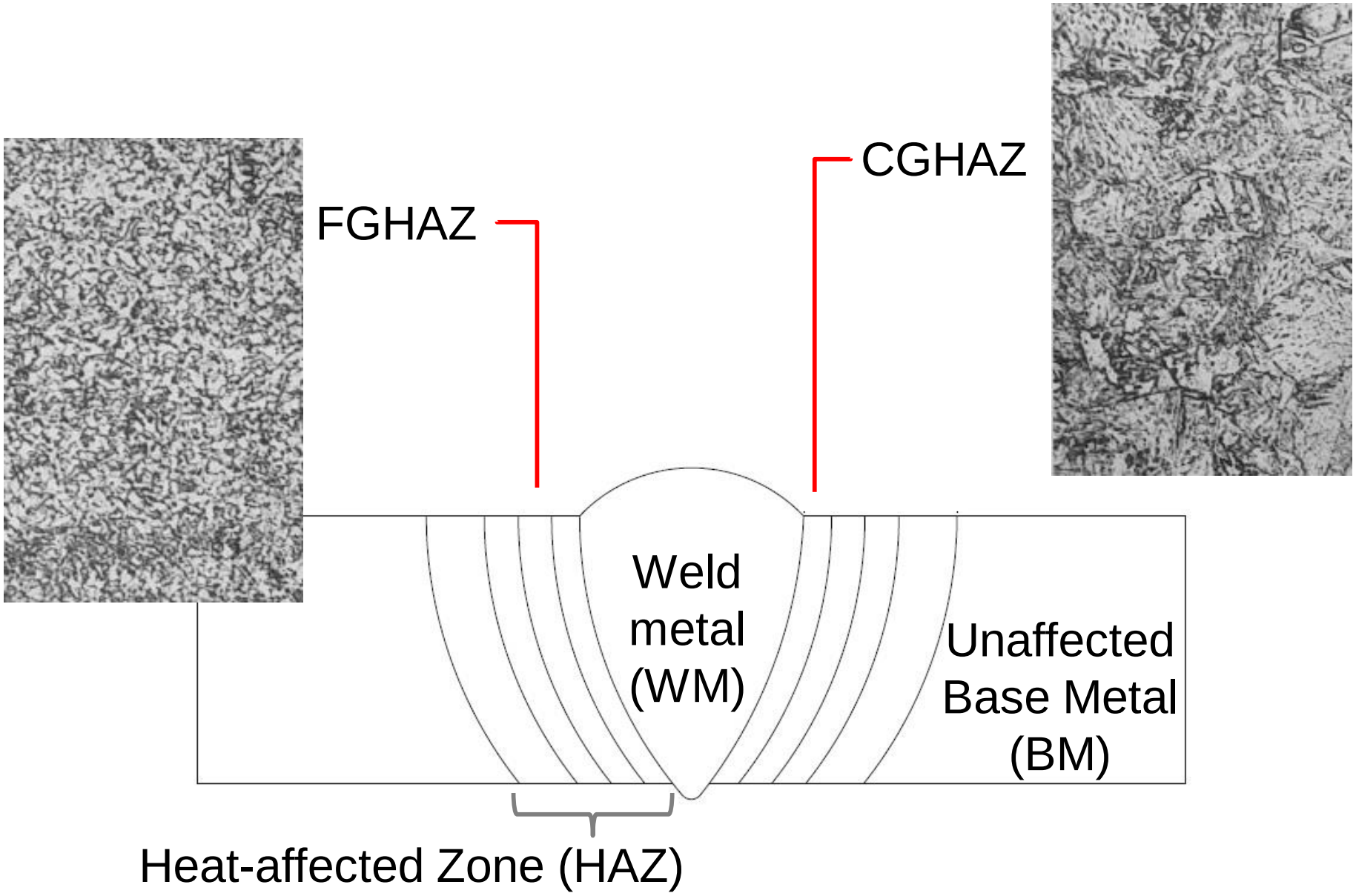
Background – Heat-Affected Zone

Heat-affected Zone: unmelted base metal near weld fusion line experiencing microstructural changes

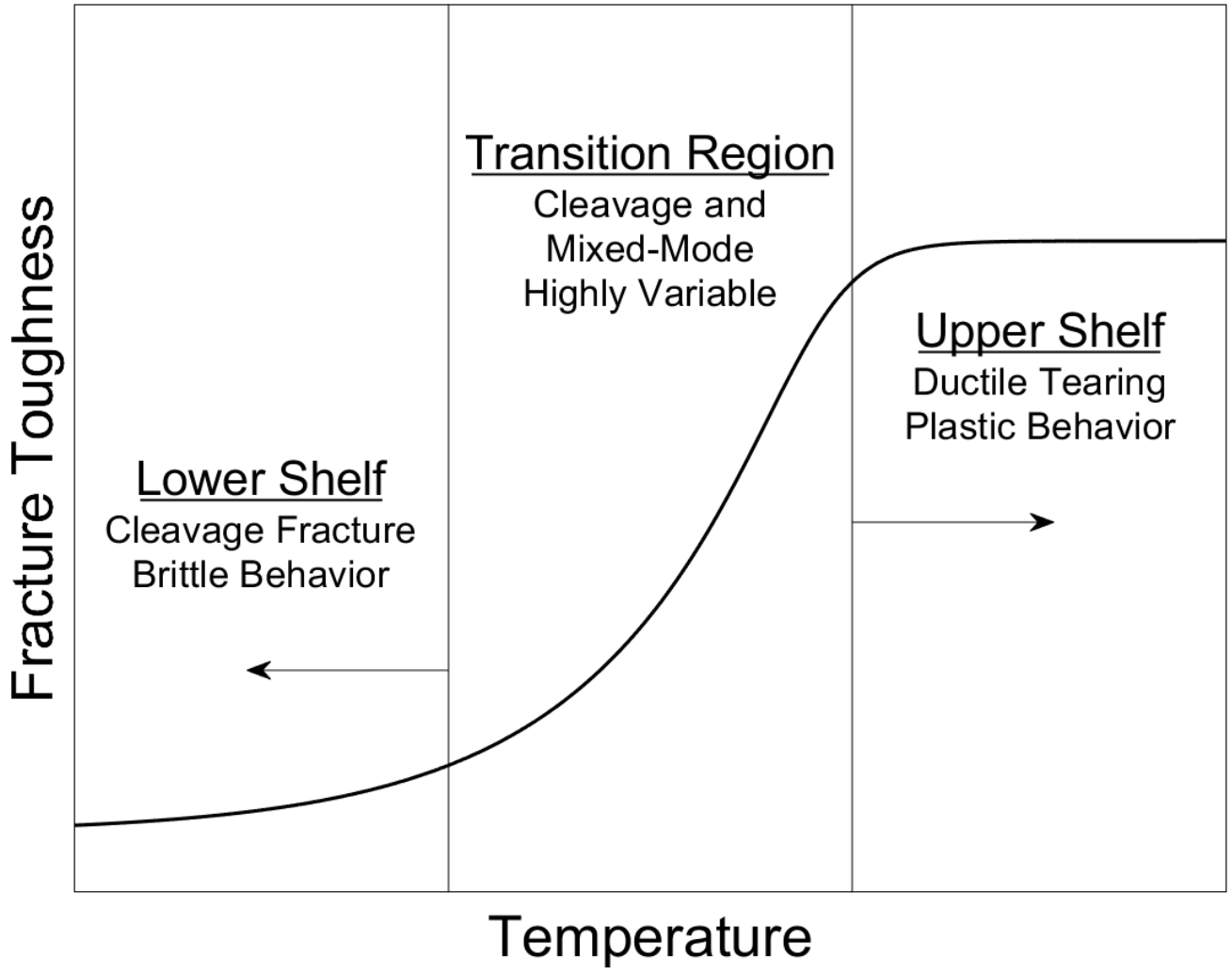


[1] Pisarski, 1984
[2] Wood, 1986

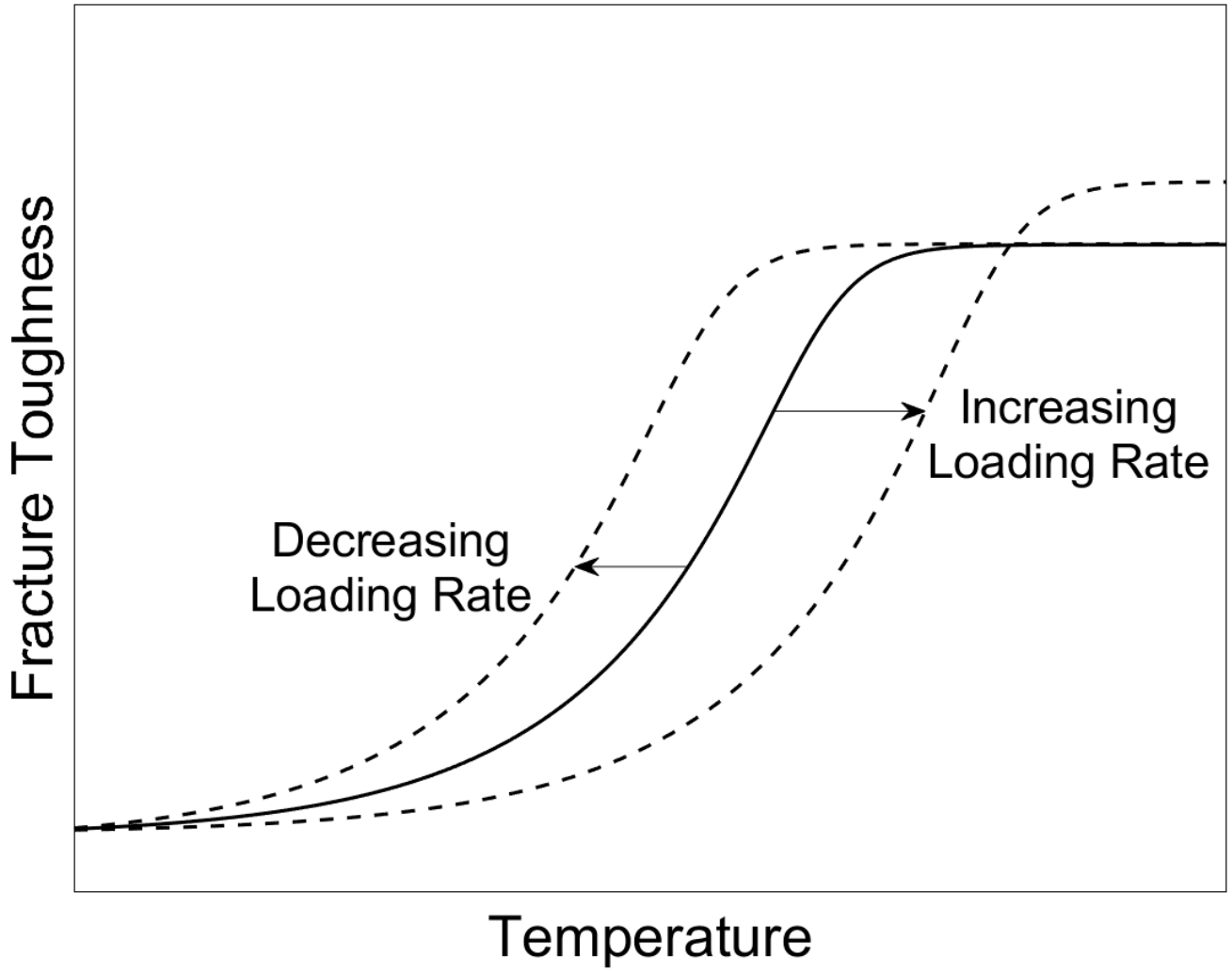
Background – Heat-Affected Zone



Background – Fracture Mechanics

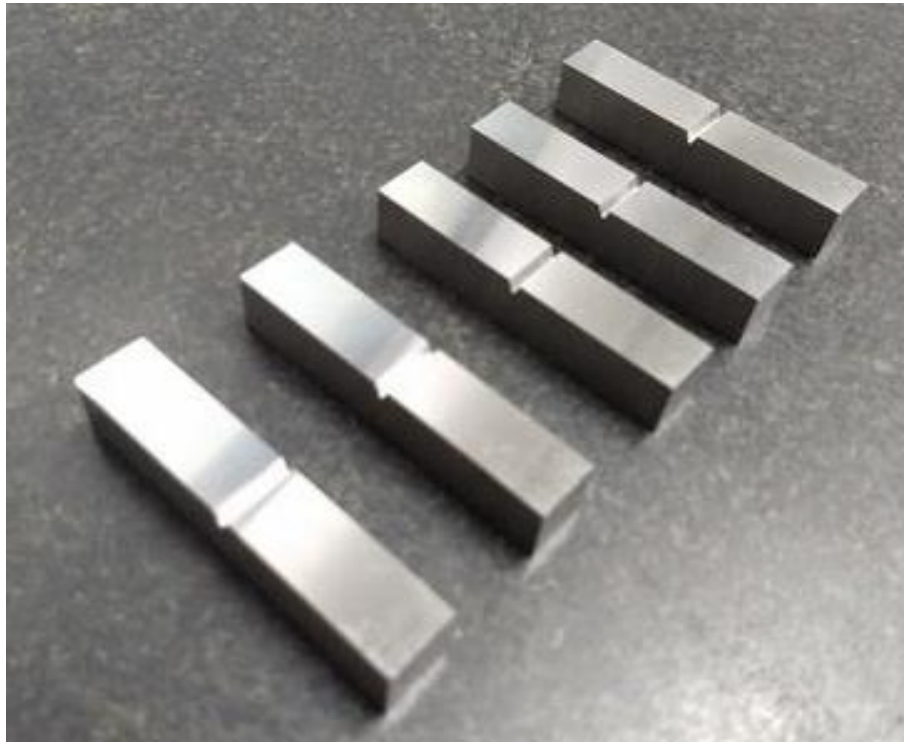


Background – Fracture Mechanics



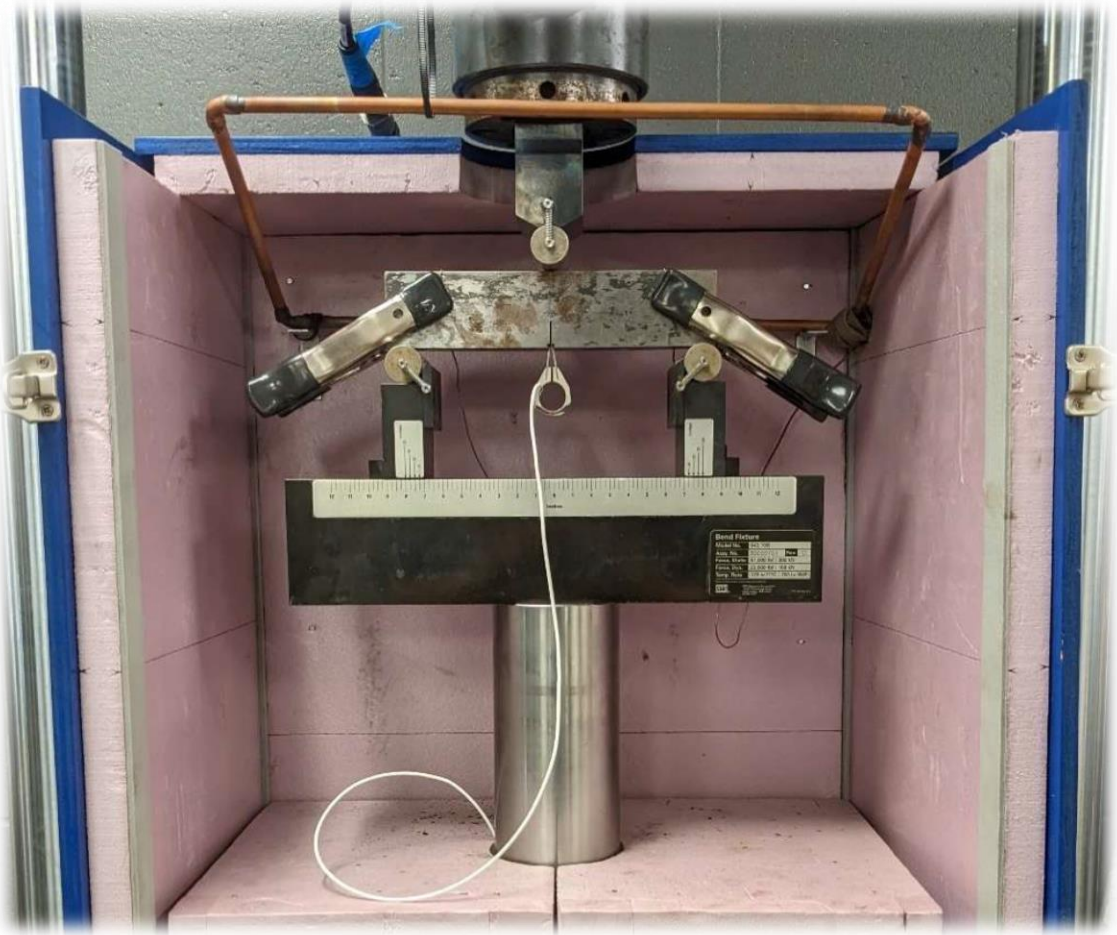
Background – Test Methods

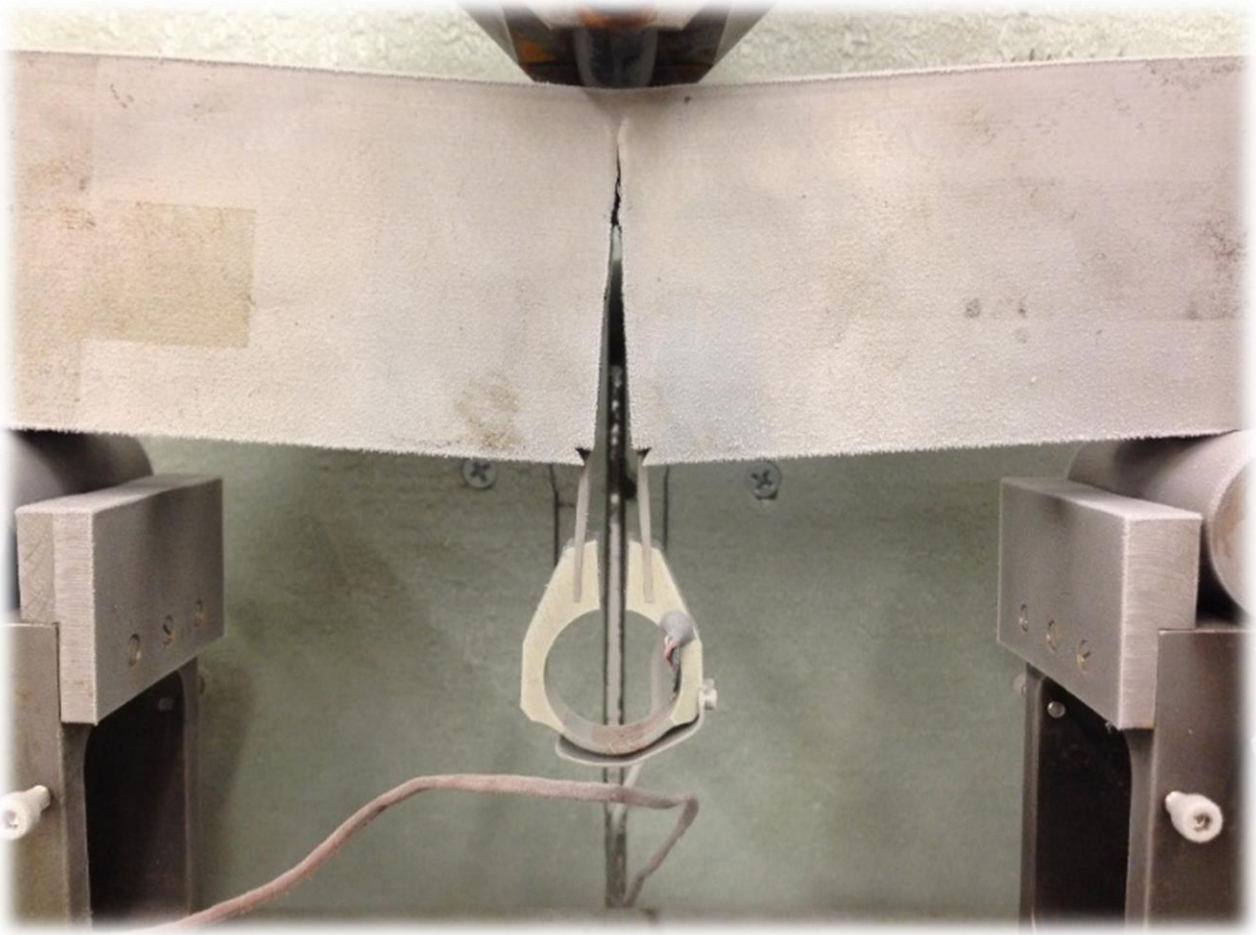
- Charpy V-Notch



Background – Test Methods

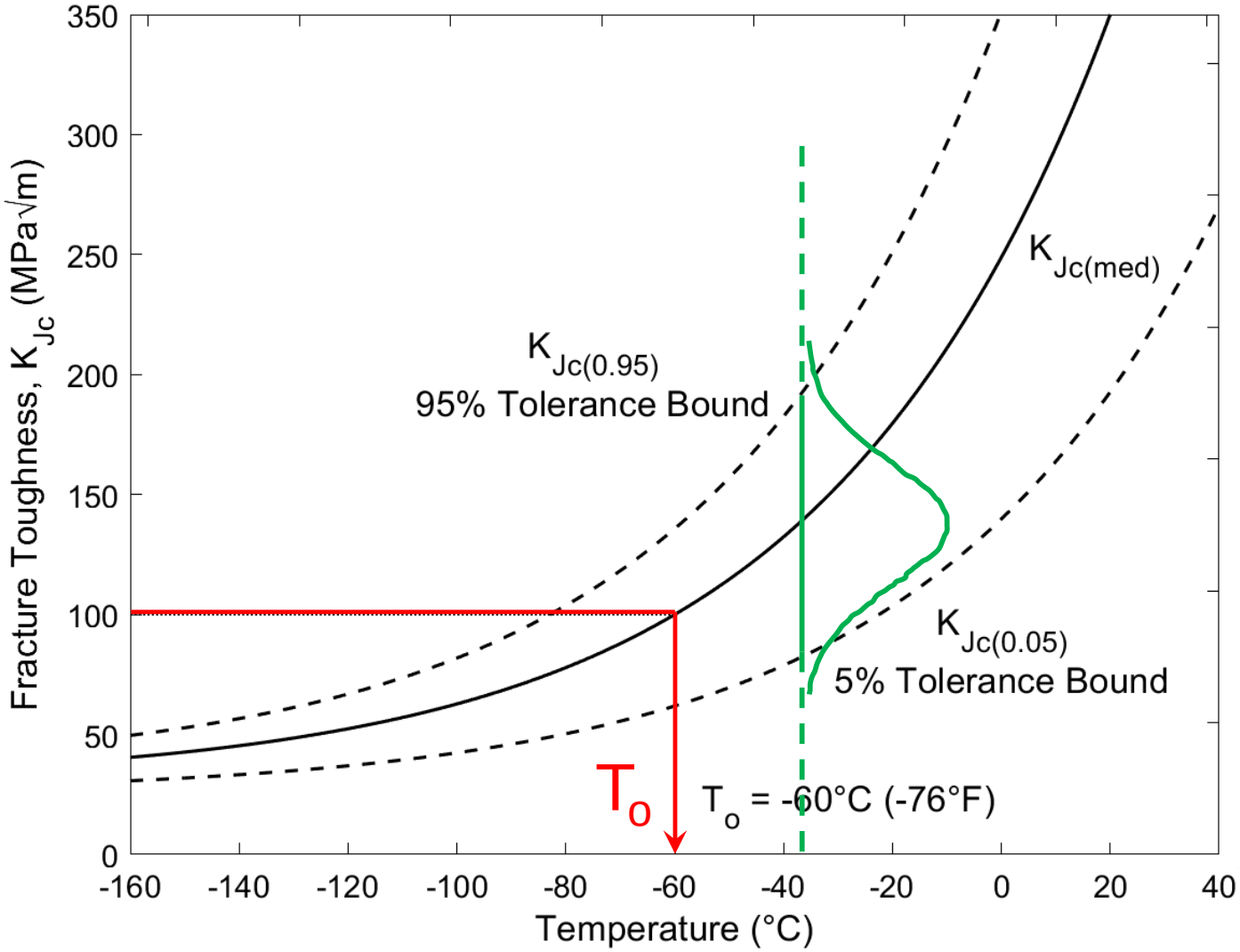
- Fracture Toughness





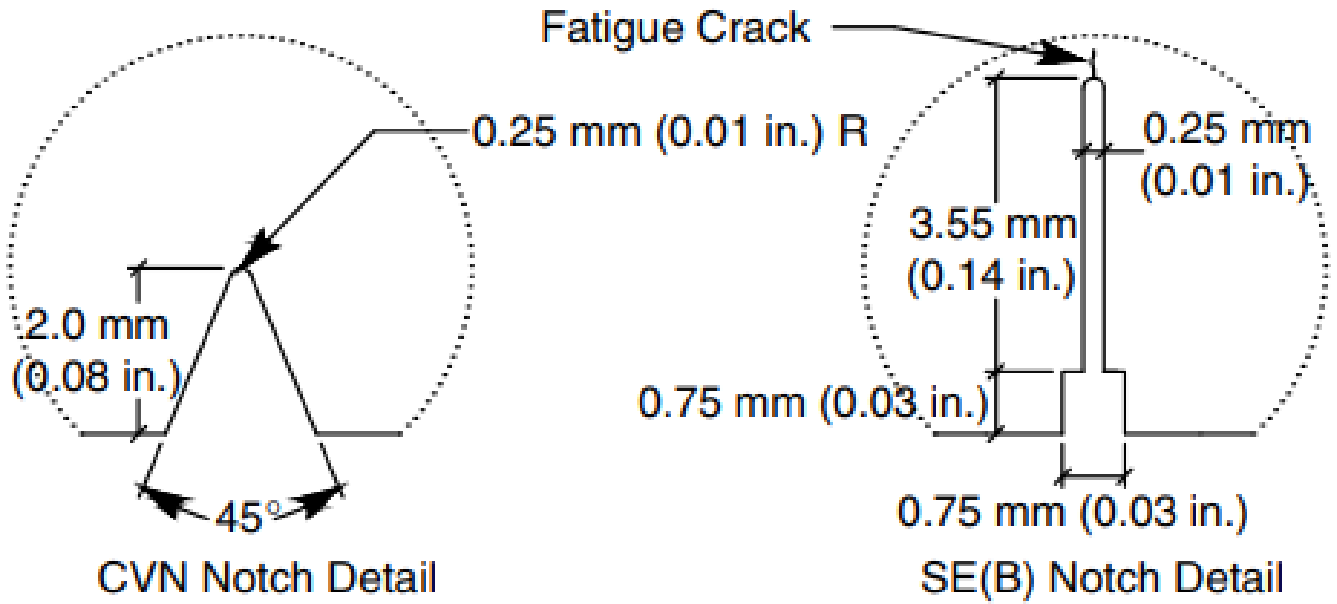
Background – Test Methods

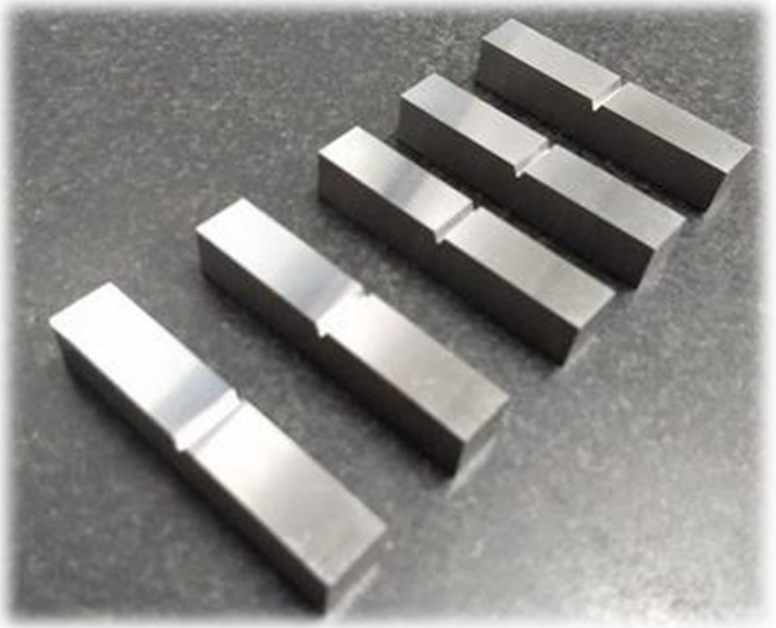
- Master Curve

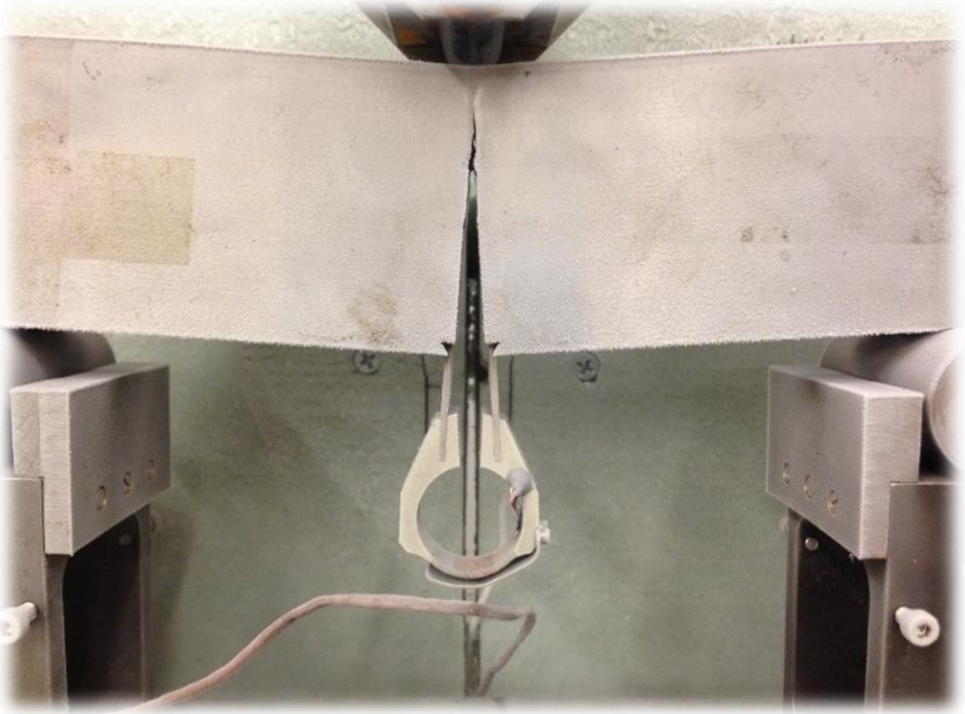


Background – CVN-K Correlation

- Fracture Toughness







Background – CVN-K Correlation

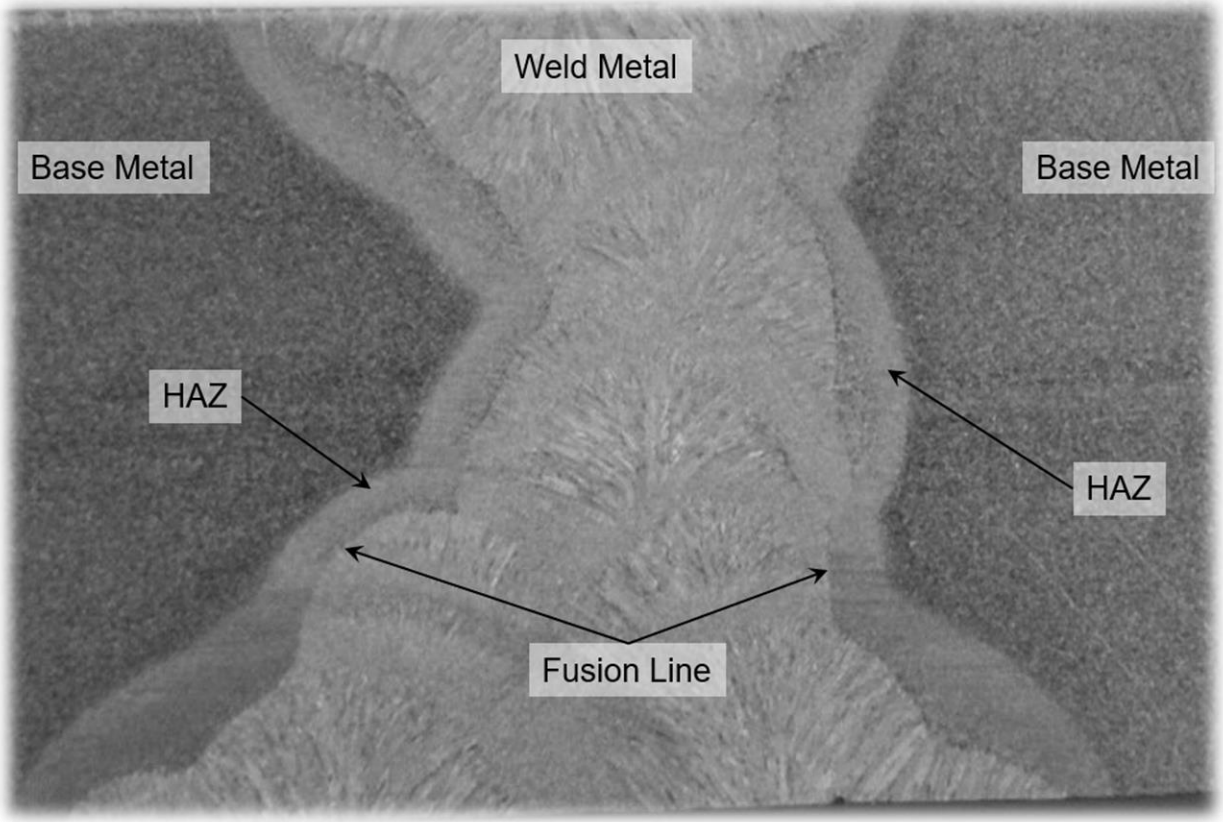
Barsom and Rolfe Two-Stage Correlation

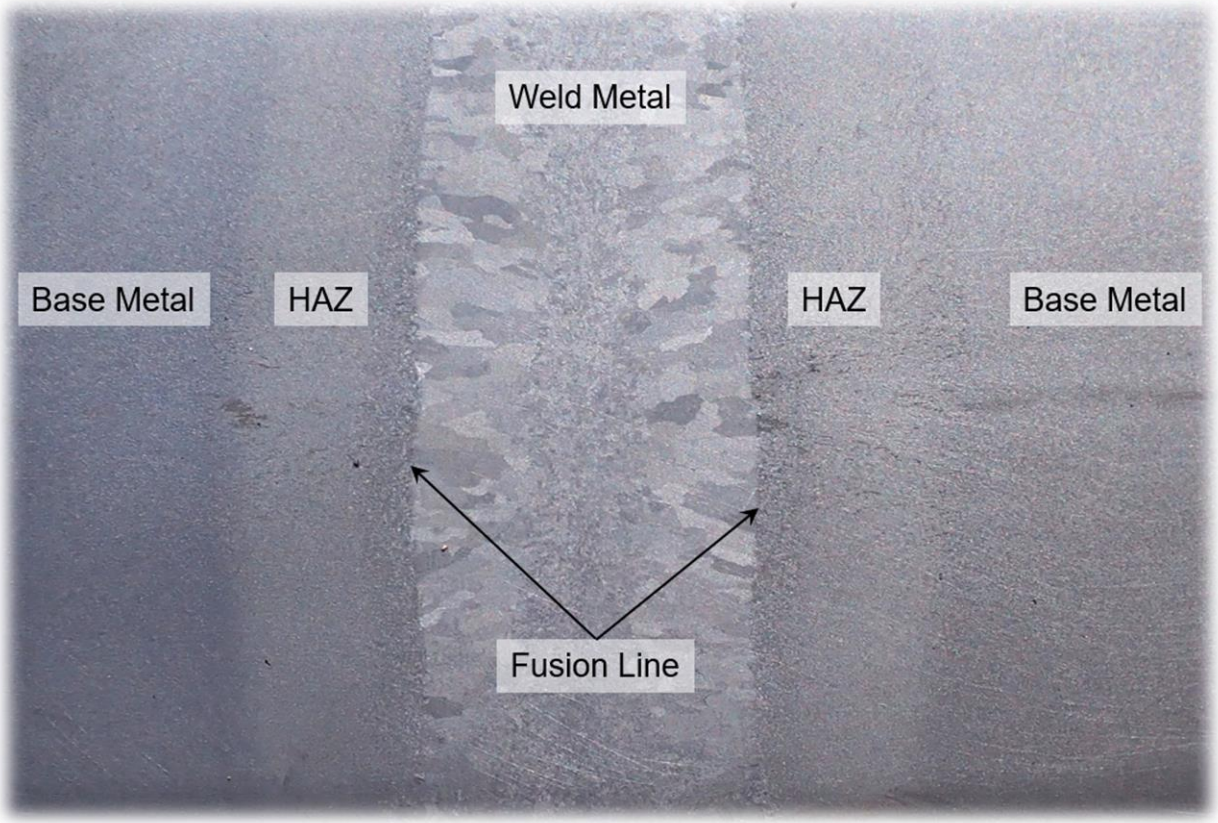
$$K_{Id} = 12\sqrt{CVN}\ (\text{ksi}\sqrt{\text{in}})$$

Rate-Dependent Temperature Shift

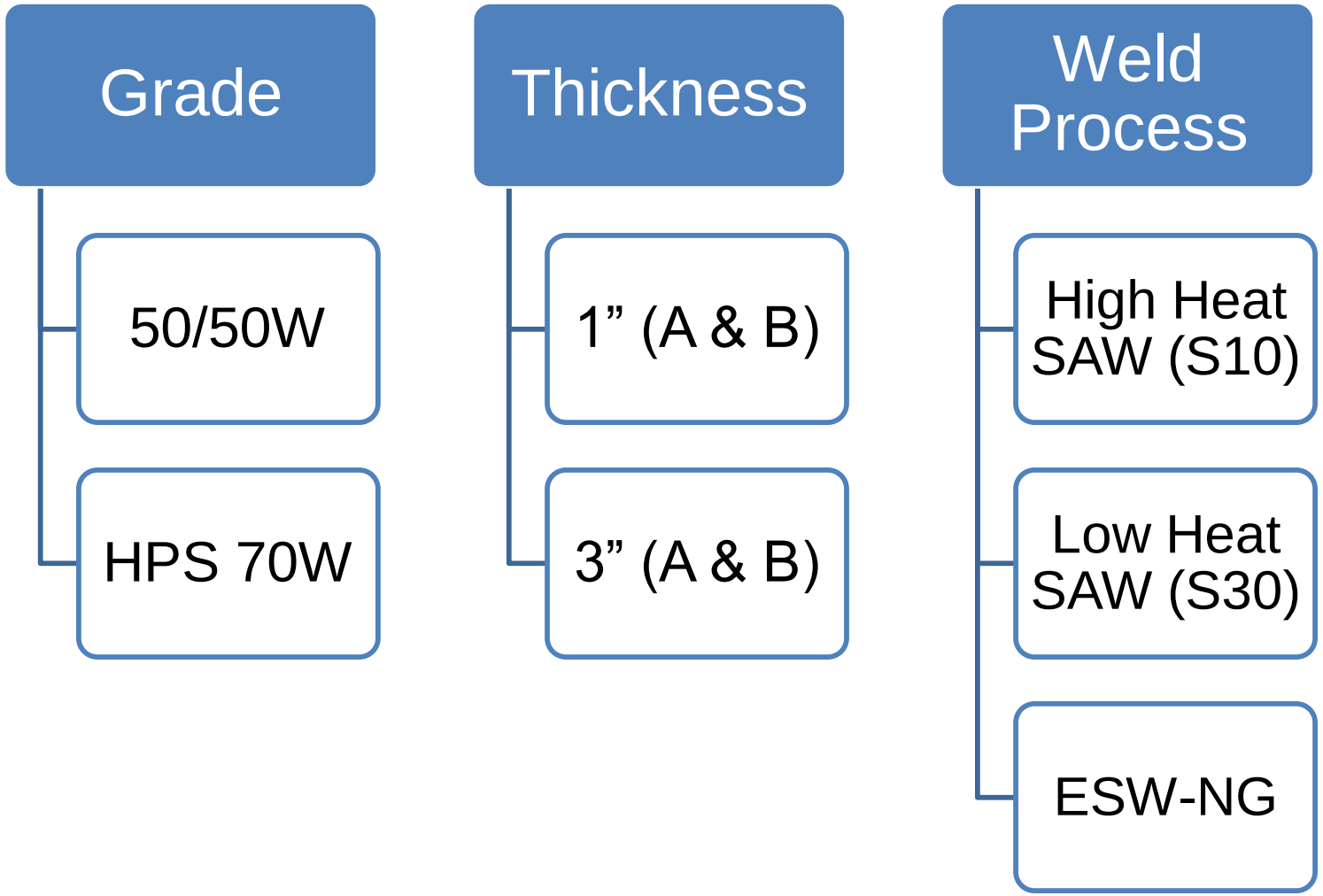
$$T_{shift} = 215\ - 1.5\sigma_y\ (°\text{F})$$

Heat-Affected Zone

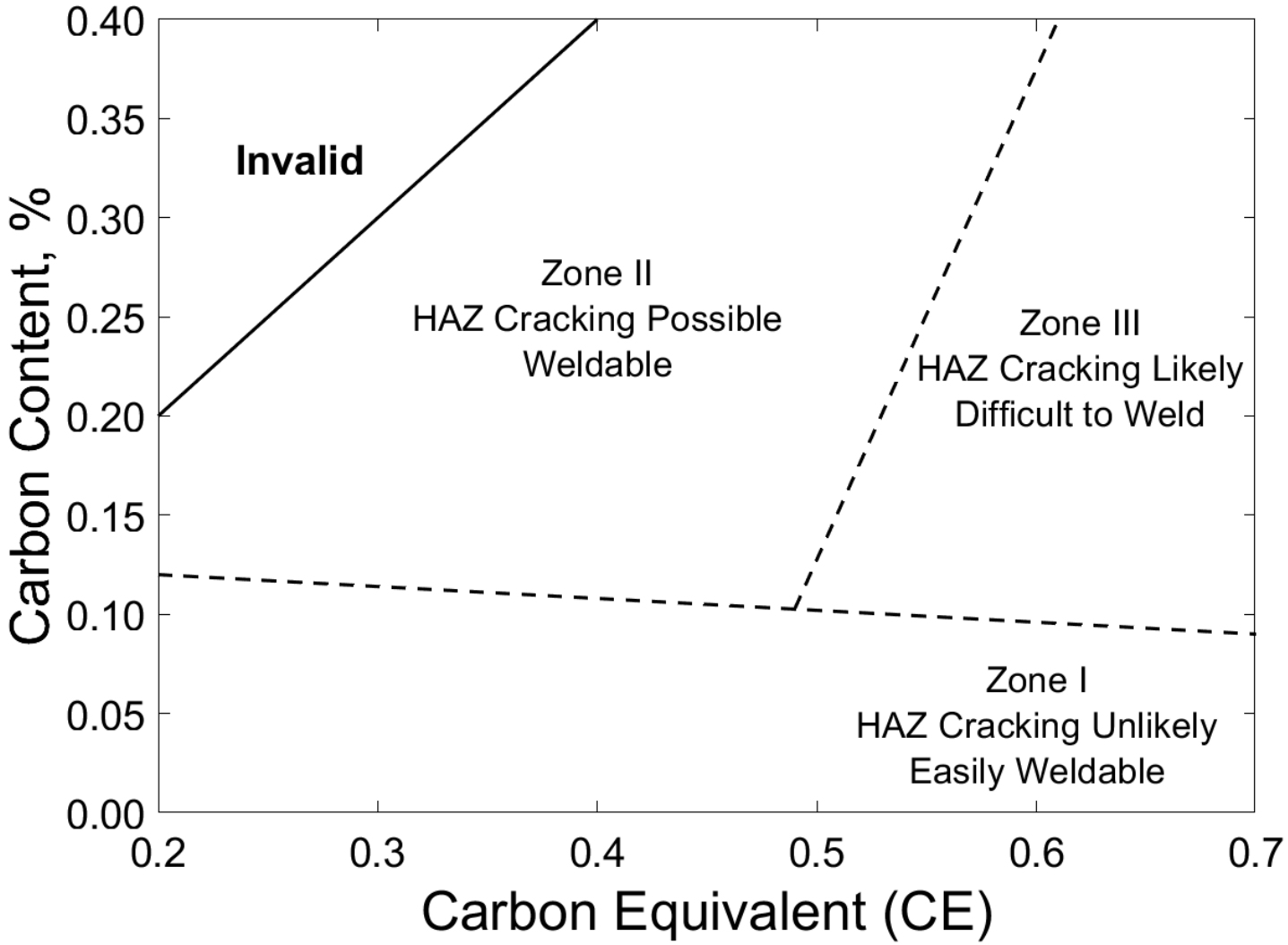




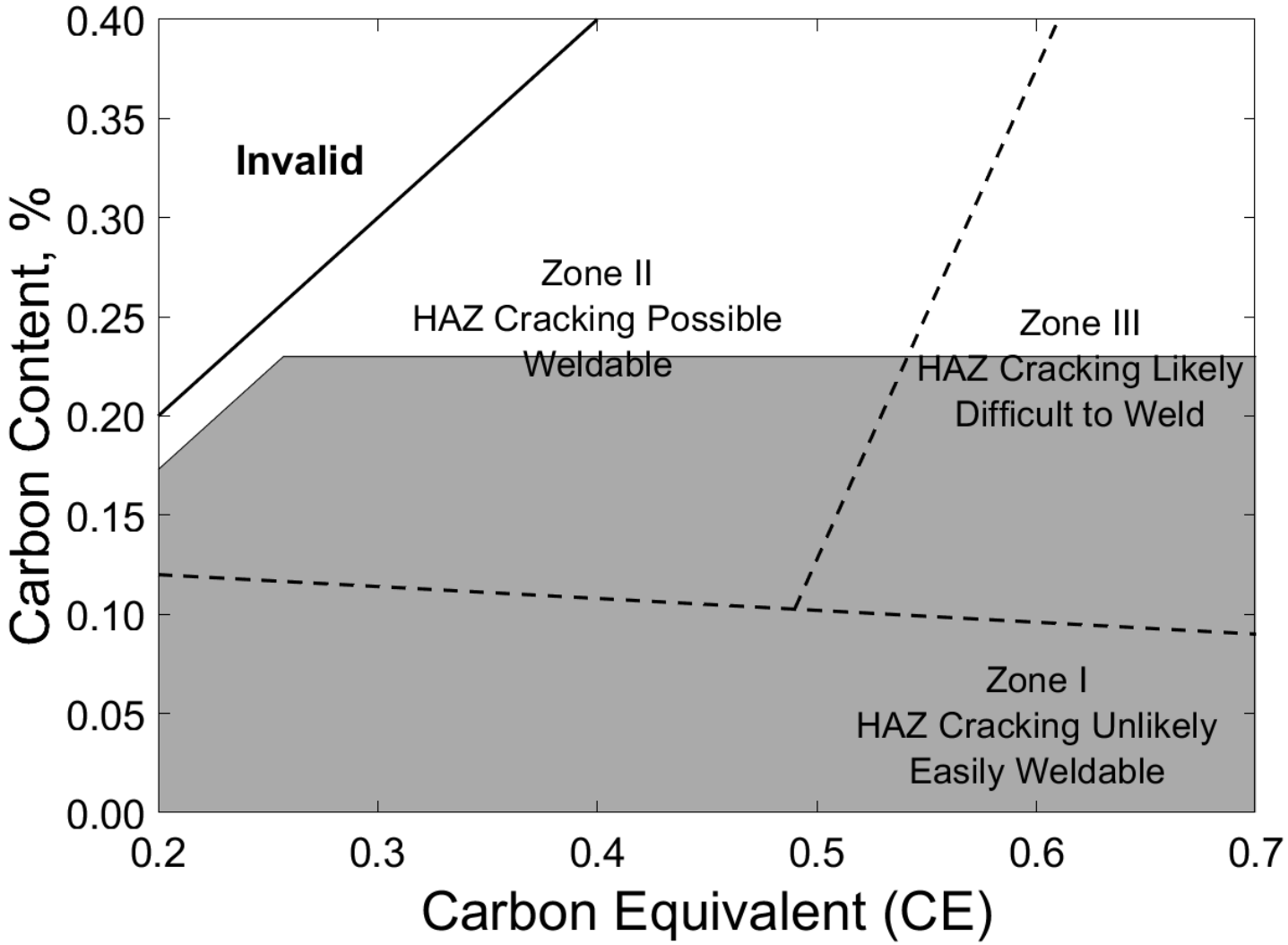
Test Matrix


Grade
50/50W
HPS 70W
Thickness
1” (A & B)
3” (A & B)
Weld Process
High Heat SAW (S10)
Low Heat SAW (S30)
ESW-NG

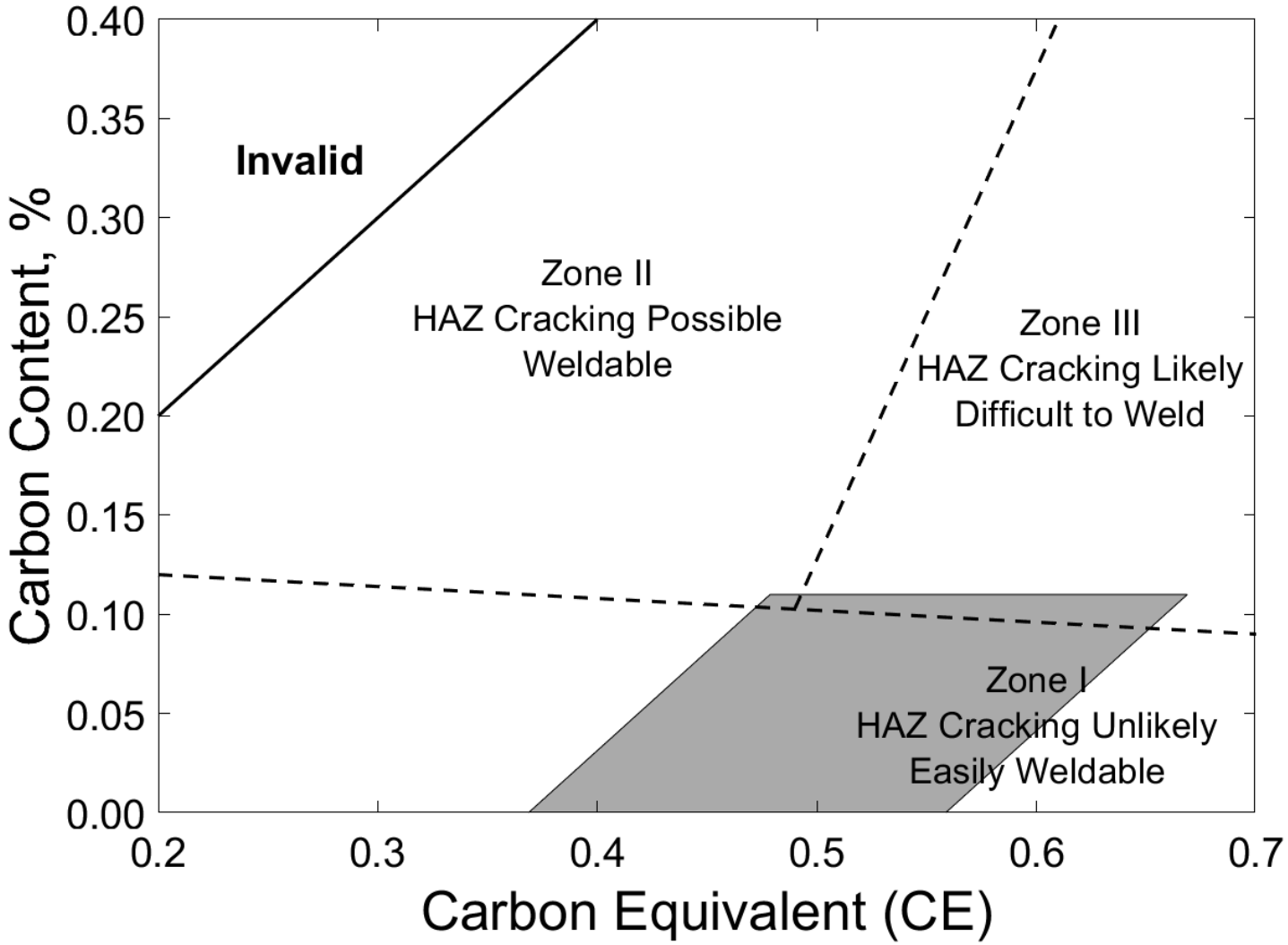
Base Metal Chemistry



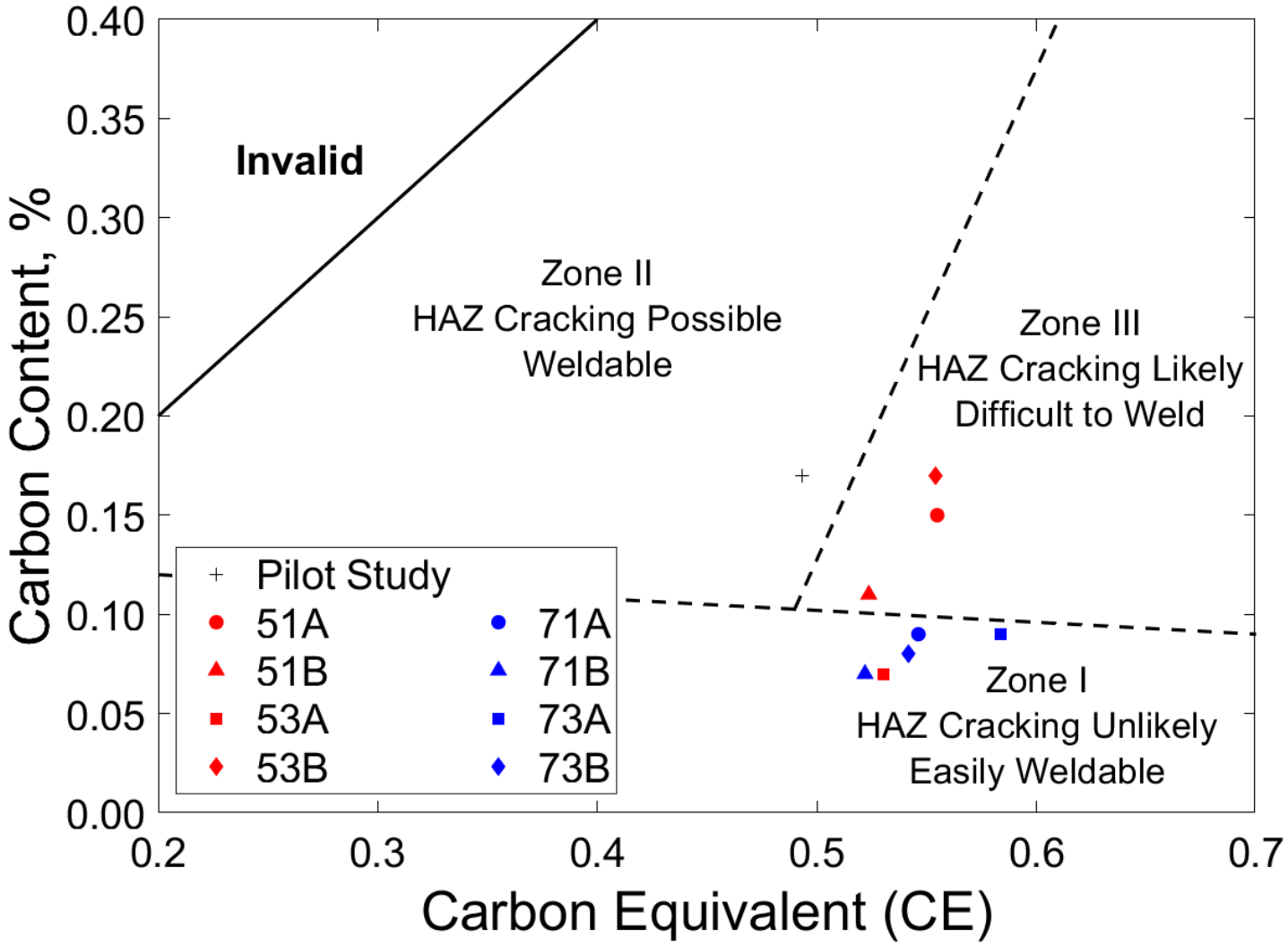
Base Metal Chemistry



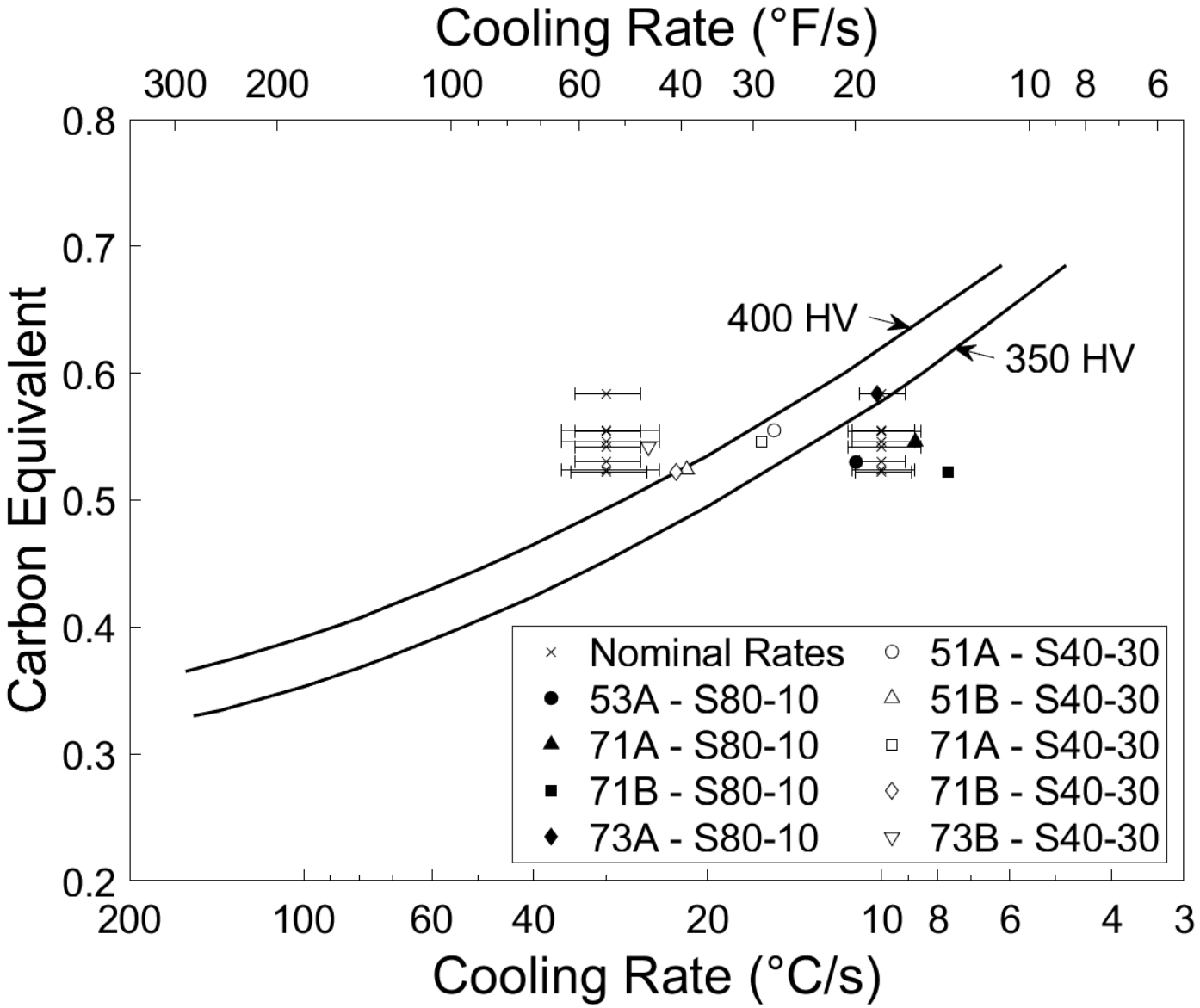
Base Metal Chemistry



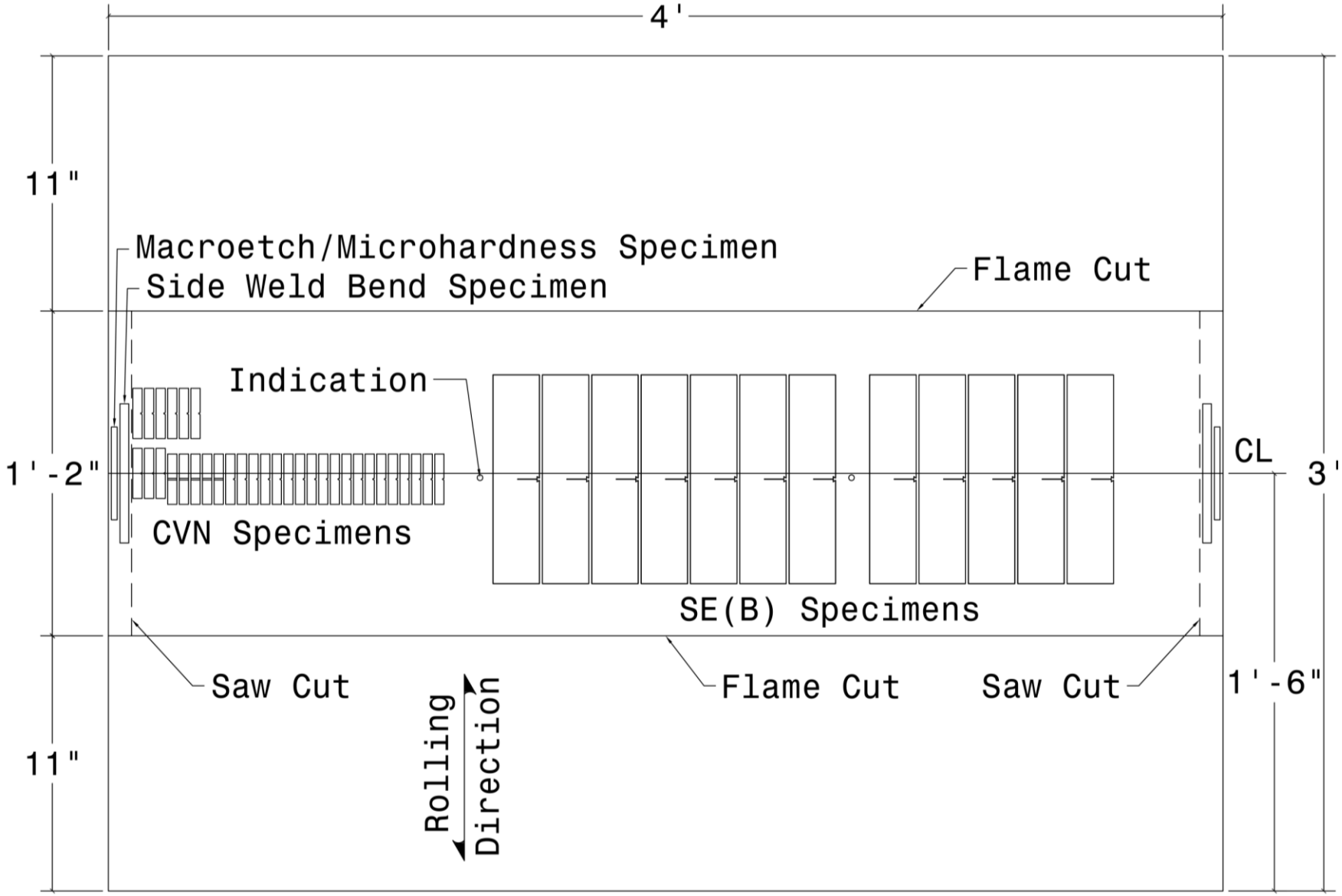
Base Metal Chemistry



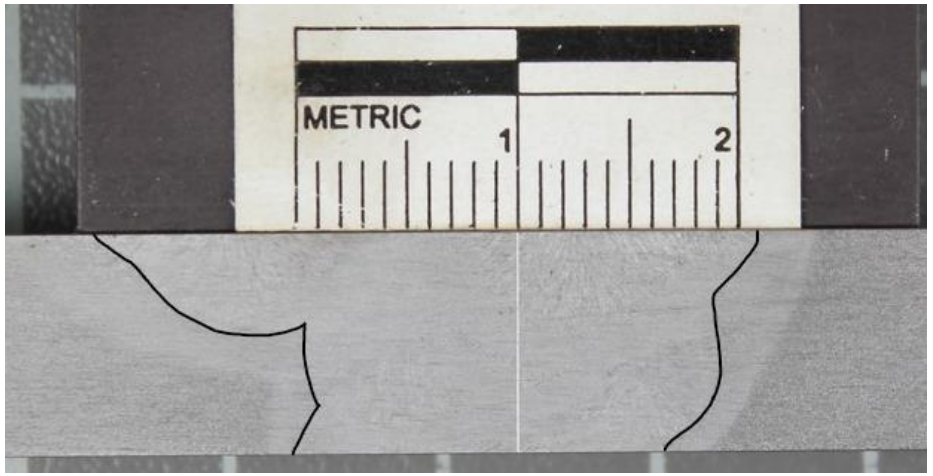
HAZ Cooling Rates

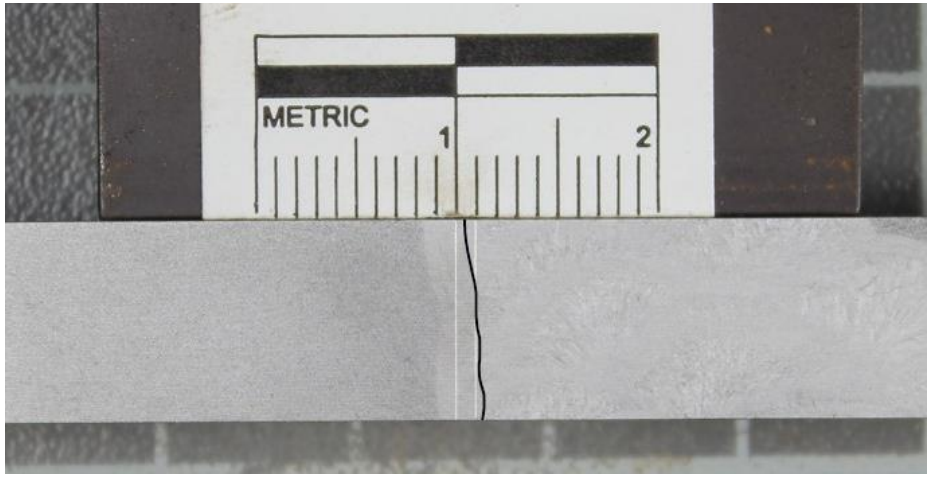


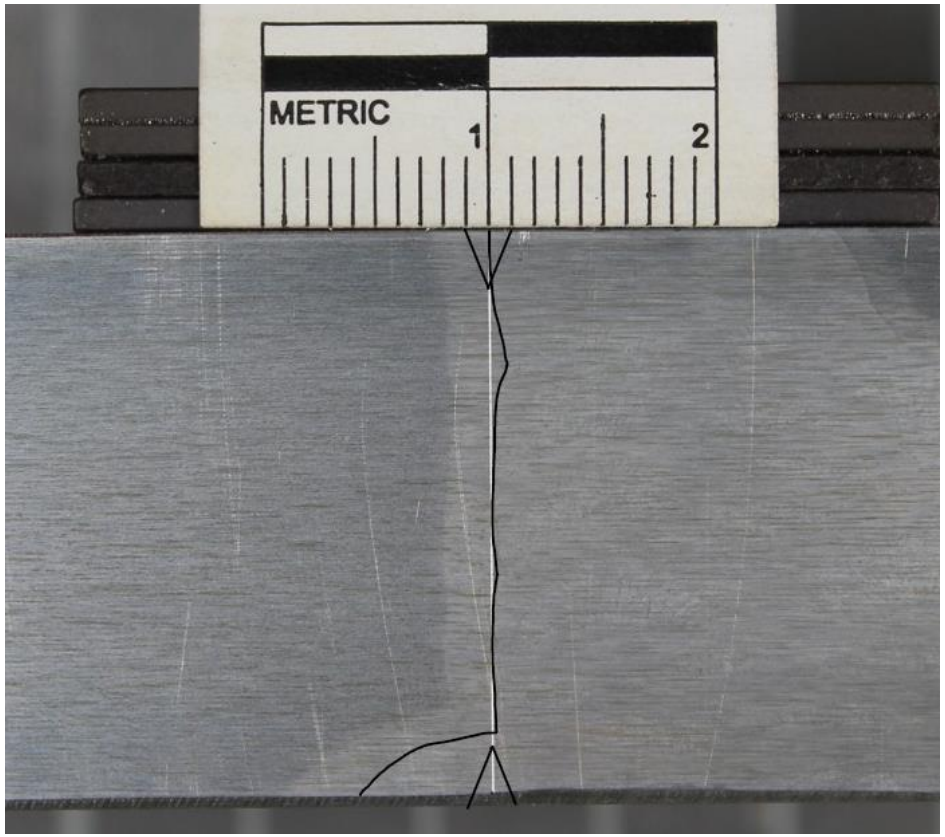
Sampling Methods



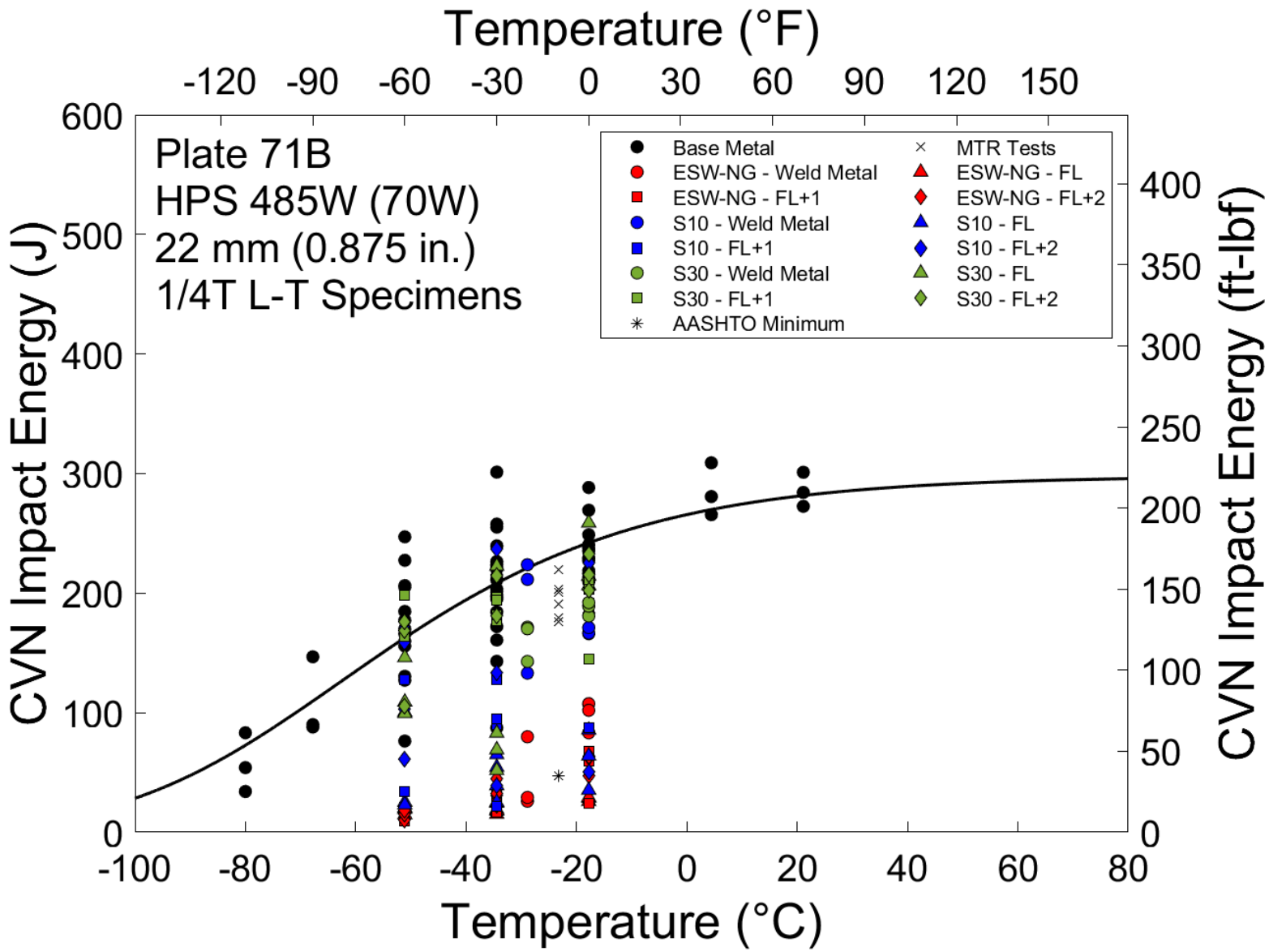
Sampling Methods



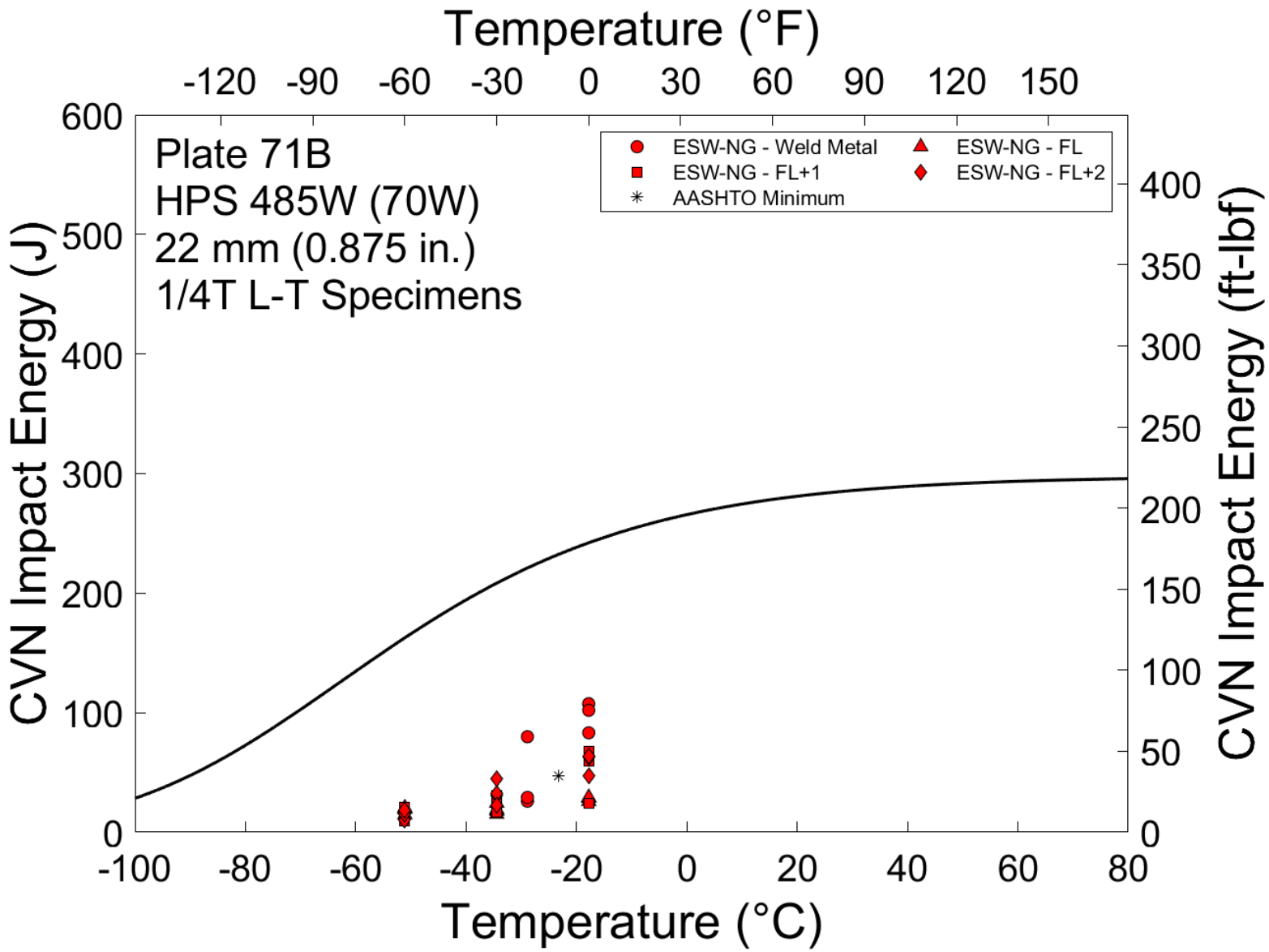




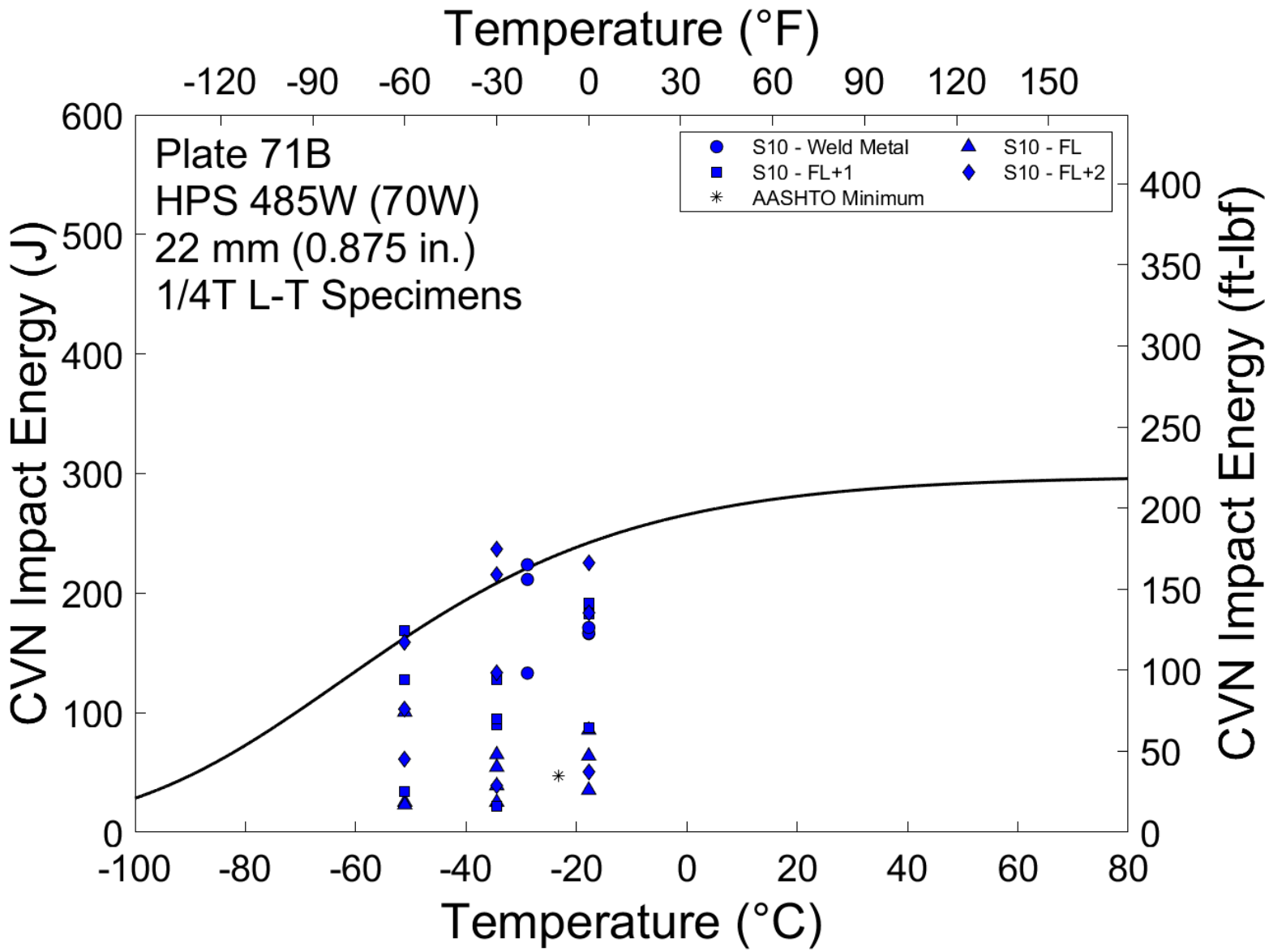
CVN Results


Temperature (°F)
-120 -90 -60 -30 0 30 60 90 120 150
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
Base Metal
ESW-NG - Weld Metal
ESW-NG - FL+1
S10 - Weld Metal
S10 - FL+1
S30 - Weld Metal
S30 - FL+1
AASHTO Minimum
MTR Tests
ESW-NG - FL
ESW-NG - FL+2
S10 - FL
S10 - FL+2
S30 - FL
S30 - FL+2
CVN Impact Energy (J)
600
500
400
300
200
100
0
CVN Impact Energy (ft-lbf)
400
350
300
250
200
150
100
50
0
-100 -80 -60 -40 -20 0 20 40 60 80
Temperature (°C)

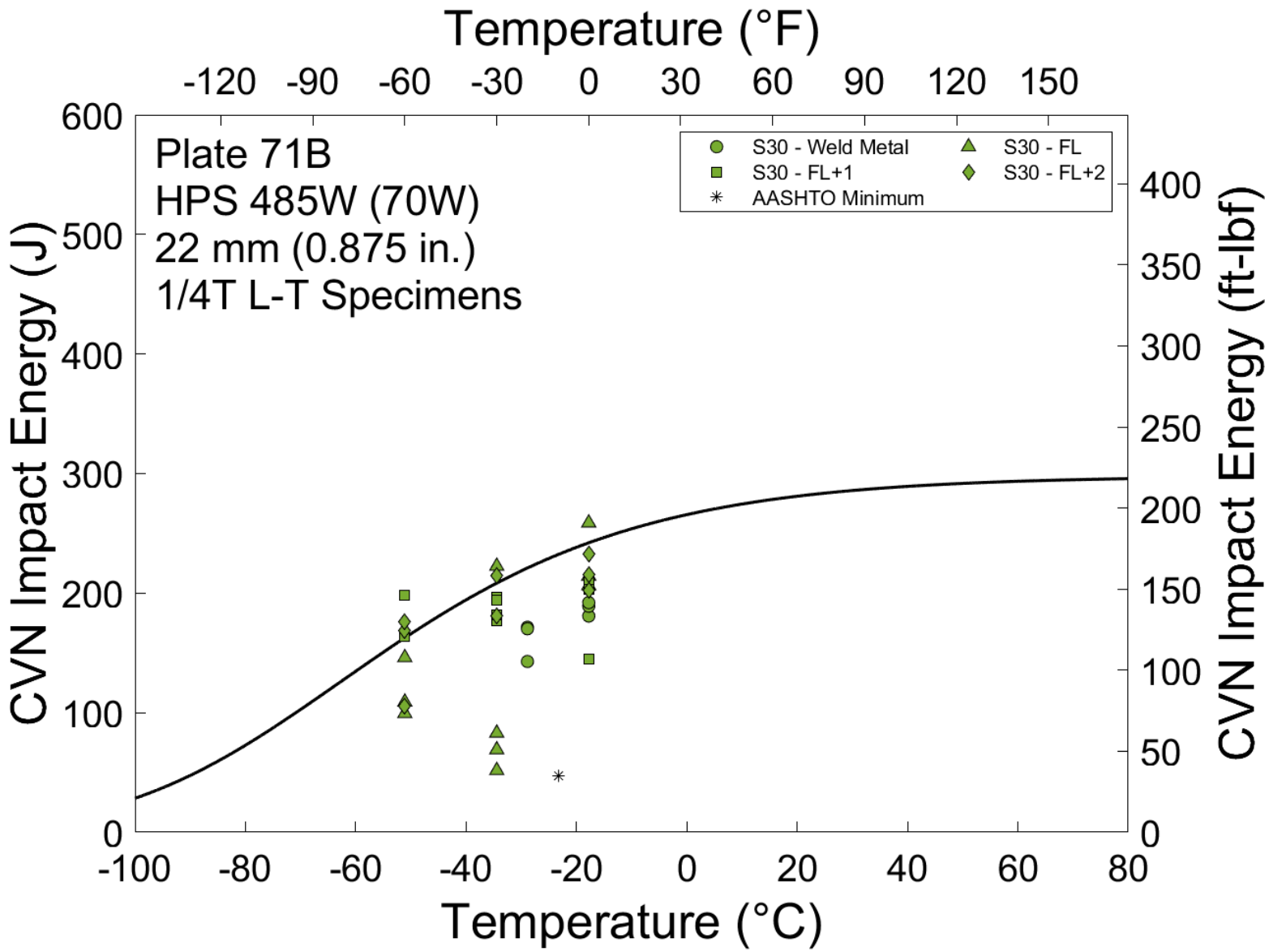
CVN Results


Temperature (°F)
-120 -90 -60 -30 0 30 60 90 120 150
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
ESW-NG - Weld Metal
ESW-NG - FL
ESW-NG - FL+1
ESW-NG - FL+2
AASHTO Minimum
CVN Impact Energy (J)
600 500 400 300 200 100 0
CVN Impact Energy (ft-lbf)
400 350 300 250 200 150 100 50 0
-100 -80 -60 -40 -20 0 20 40 60 80
Temperature (°C)

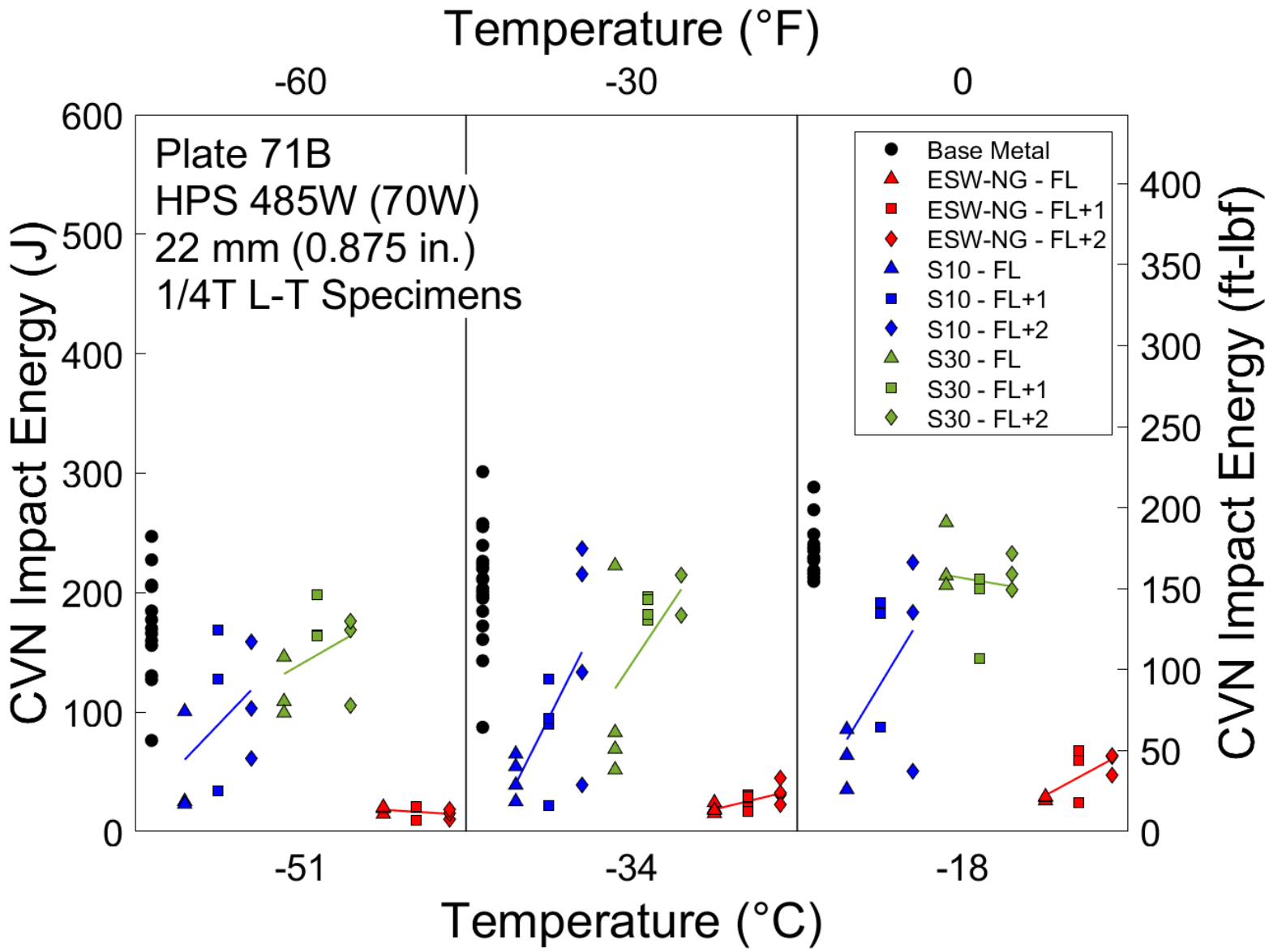
CVN Results


Temperature (°F)
-120 -90 -60 -30 0 30 60 90 120 150
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
S10 - Weld Metal
S10 - FL
S10 - FL+1
S10 - FL+2
AASHTO Minimum
CVN Impact Energy (J)
600 500 400 300 200 100 0
CVN Impact Energy (ft-lbf)
400 350 300 250 200 150 100 50 0
-100 -80 -60 -40 -20 0 20 40 60 80
Temperature (°C)

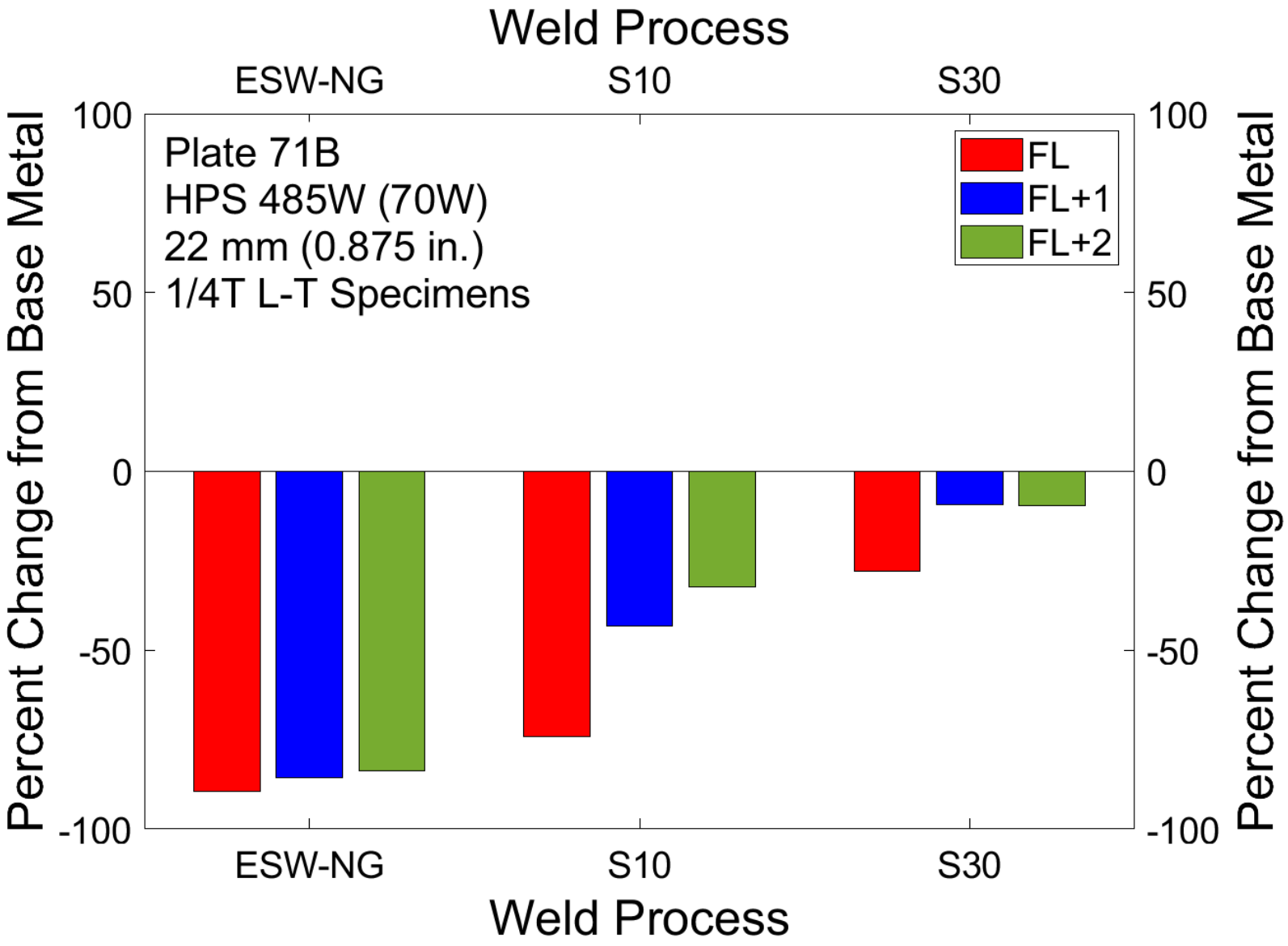
CVN Results


Temperature (°F)
-120 -90 -60 -30 0 30 60 90 120 150
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
S30 - Weld Metal
S30 - FL
S30 - FL+1
S30 - FL+2
AASHTO Minimum
CVN Impact Energy (J)
0 100 200 300 400 500 600
CVN Impact Energy (ft-lbf)
0 50 100 150 200 250 300 350 400
-100 -80 -60 -40 -20 0 20 40 60 80
Temperature (°C)

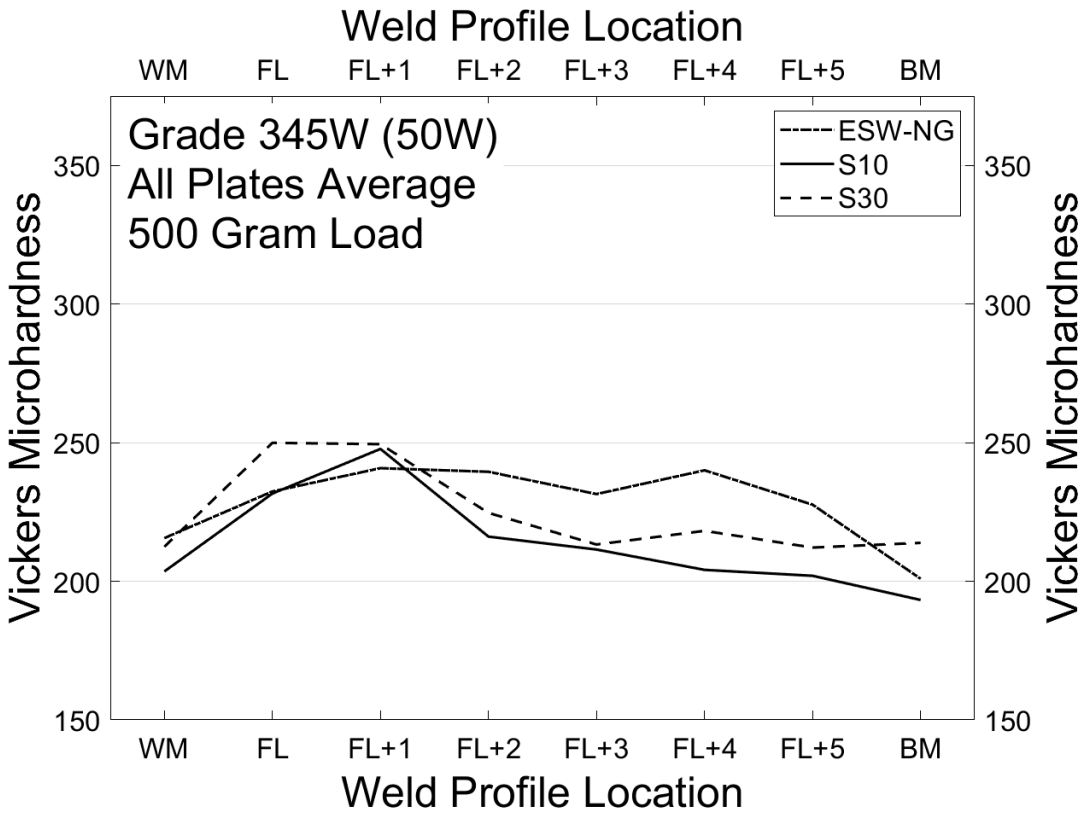
CVN Results

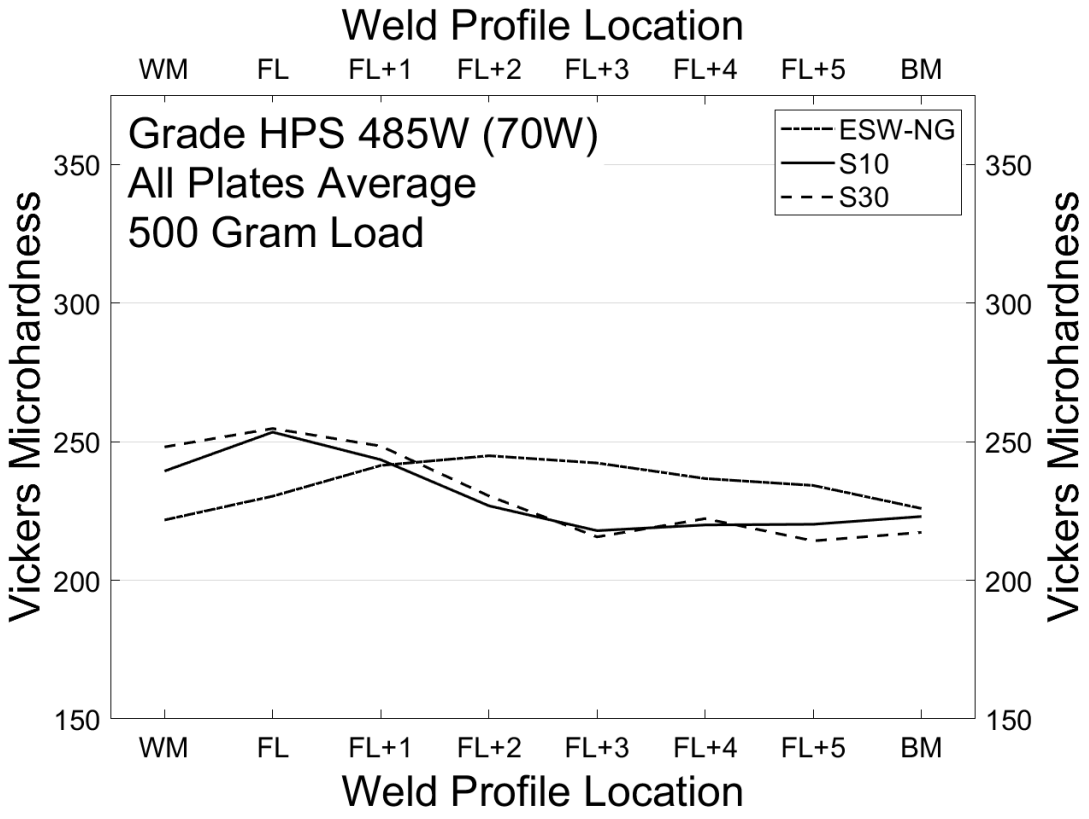

Temperature (°F)
-60
-30
0
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
Base Metal
ESW-NG - FL
ESW-NG - FL+1
ESW-NG - FL+2
S10 - FL
S10 - FL+1
S10 - FL+2
S30 - FL
S30 - FL+1
S30 - FL+2
CVN Impact Energy (J)
600
500
400
300
200
100
0
CVN Impact Energy (ft-lbf)
400
350
300
250
200
150
100
50
0
-51
-34
-18
Temperature (°C)

CVN Results

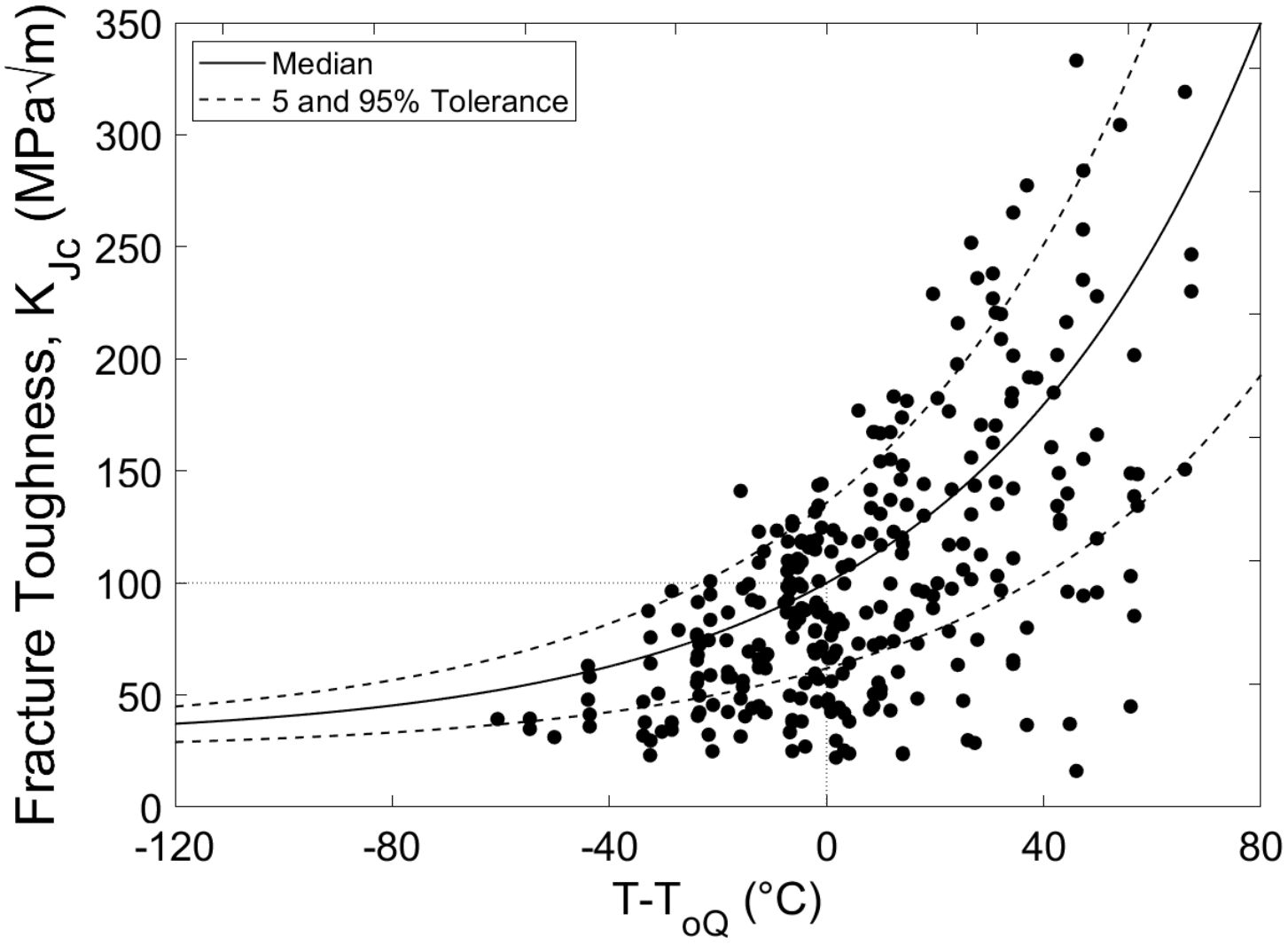

Weld Process
ESW-NG
S10
S30
Plate 71B
HPS 485W (70W)
22 mm (0.875 in.)
1/4T L-T Specimens
FL
FL+1
FL+2
Percent Change from Base Metal
100
50
0
-50
-100
Weld Process

Vickers Microhardness Results

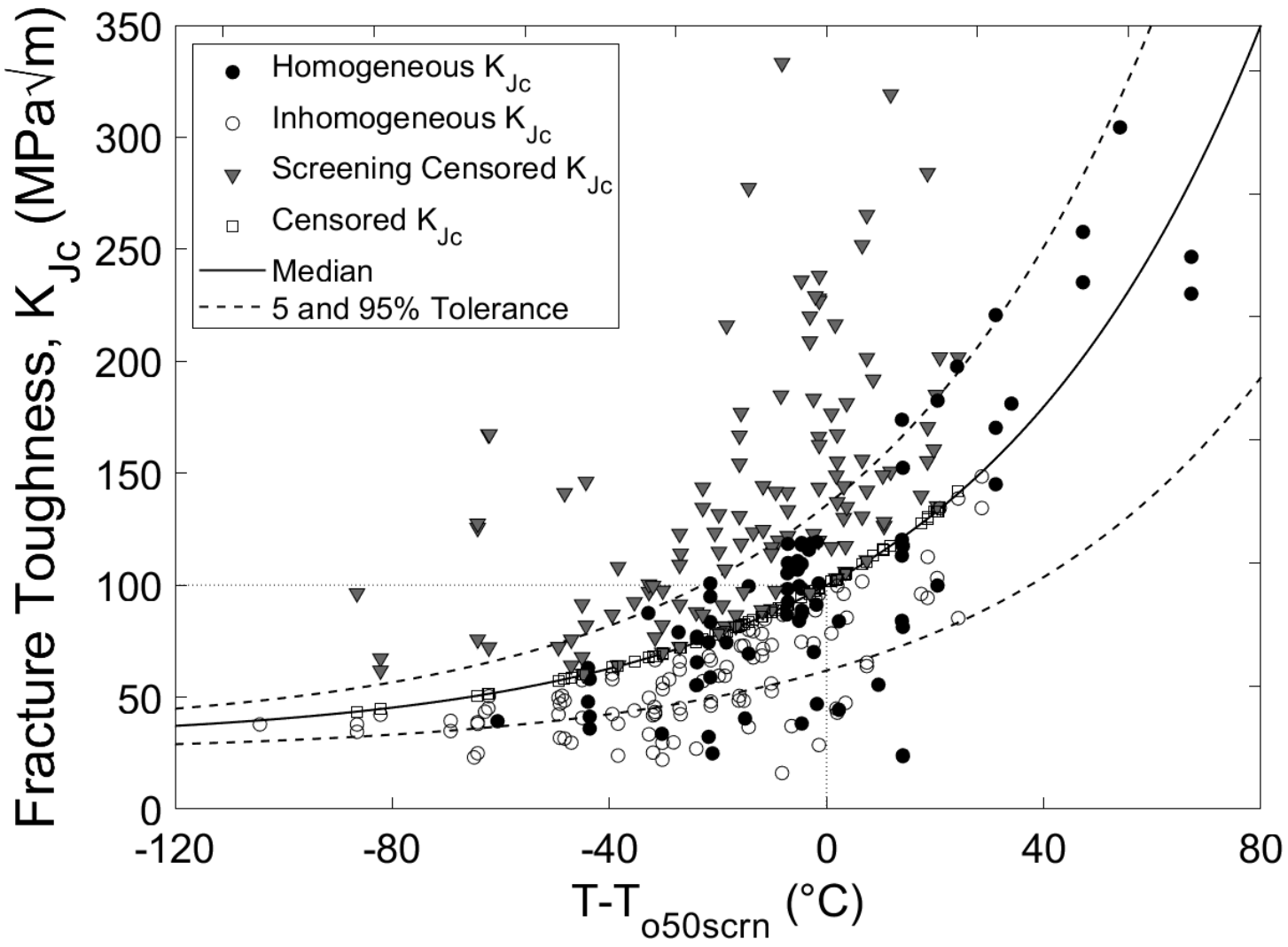




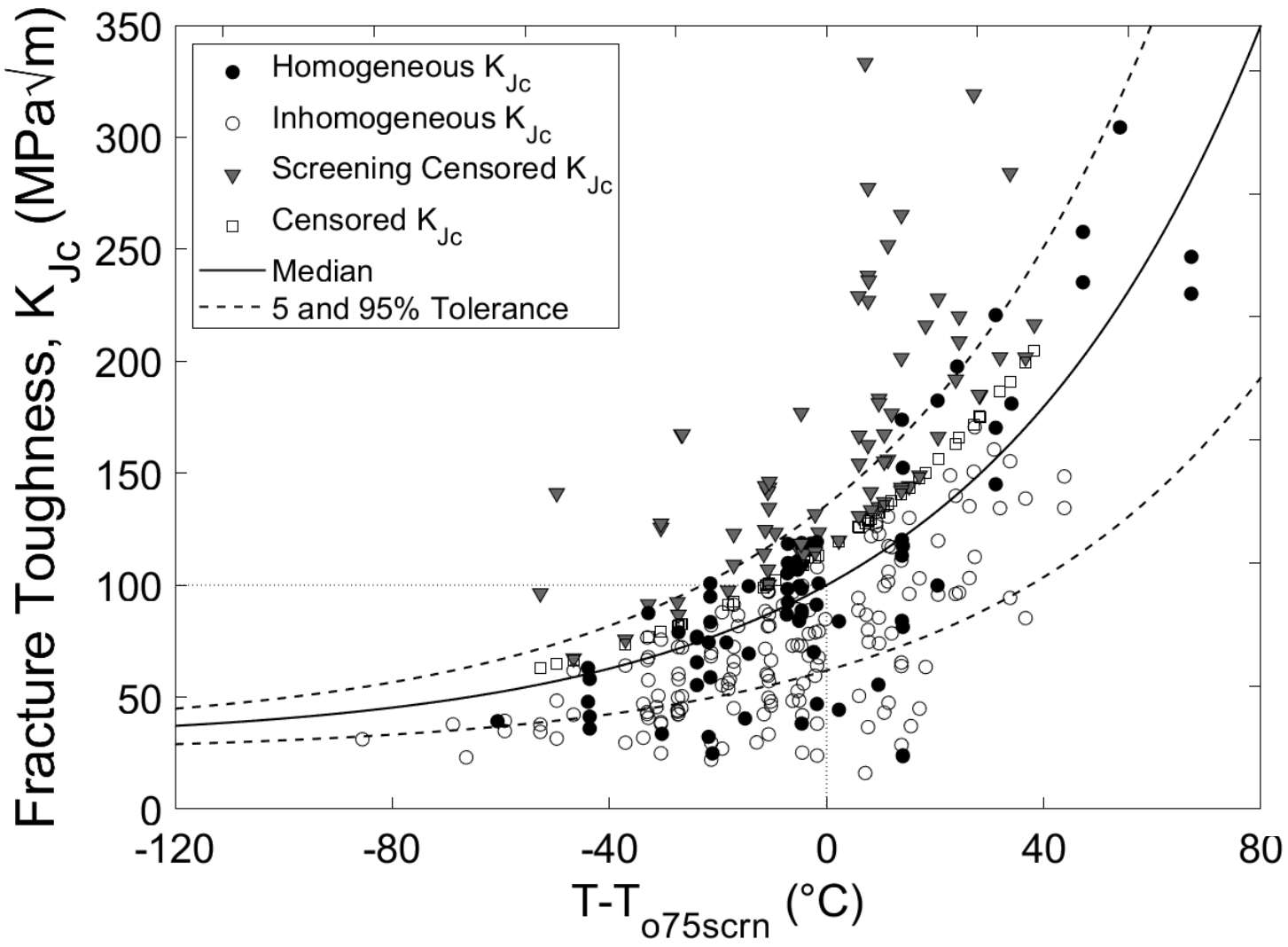
Fracture Toughness Results



Fracture Toughness Results



Fracture Toughness Results



Historically-Accepted Toughness

Fracture Critical Applications

Steel Grade	Thickness, mm (in.)	Minimum Average Energy, J (ft-lbf)		
		Zone I	Zone II	Zone III
345 (50), 345S (50S), 345W (50W)	to 50 (2) incl.	34 (25) at 21°C (70°F)	34 (25) at 4°C (40°F)	34 (25) at -12°C (10°F)
	over 50 to 100 (2 to 4) incl.	41 (30) at 21°C (70°F)	41 (30) at 4°C (40°F)	41 (30) at -12°C (10°F)
HPS 485W (HPS 70W)	to 100 (4) incl.	48 (35) at -23°C (-10°F)	48 (35) at -23°C (-10°F)	48 (35) at -23°C (-10°F)

AASHTO LRFD BDS

Historically-Accepted Toughness

Non-Fracture Critical Applications

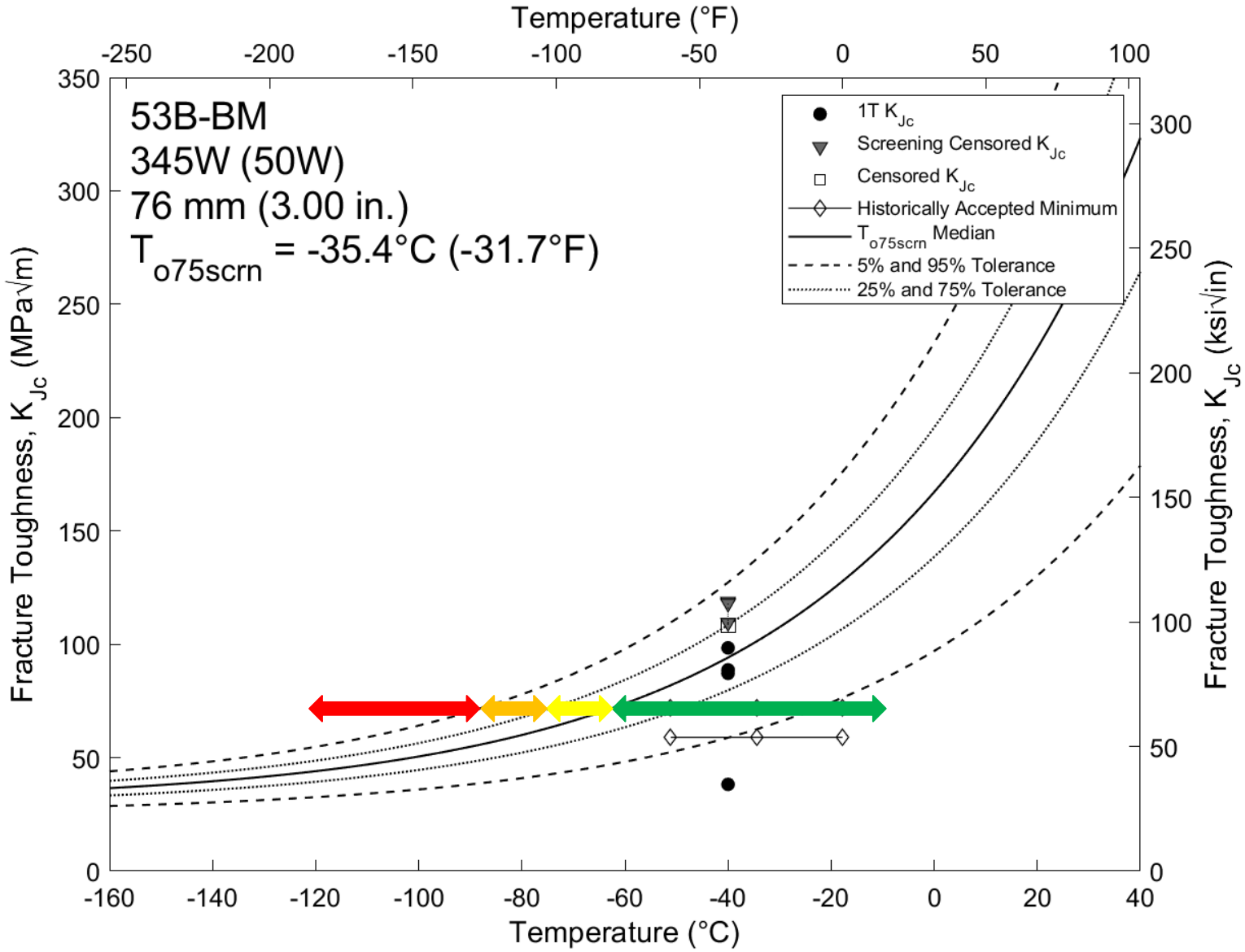
Steel Grade	Thickness, mm (in.)	Minimum Average Energy, J (ft-lbf)		
		Zone I	Zone II	Zone III
345 (50), 345S (50S), 345W (50W)	to 50 (2) incl.	20 (15) at 21°C (70°F)	20 (15) at 4°C (40°F)	20 (15) at -12°C (10°F)
	over 50 to 100 (2 to 4) incl.	27 (20) at 21°C (70°F)	27 (20) at 4°C (40°F)	27 (20) at -12°C (10°F)
HPS 485W (HPS 70W)	to 100 (4) incl.	34 (25) at -23°C (-10°F)	34 (25) at -23°C (-10°F)	34 (25) at -23°C (-10°F)

AASHTO LRFD BDS

Historically-Accepted Toughness

Steel Grade	Thickness, mm (in.)	Historically-Accepted Intermediate Rate Fracture Toughness, MPa√m (ksi√in)	
		Fracture Critical	Non-Fracture Critical
345 (50), 345S (50S), 345W (50W)	to 50 (2) incl.	66 (60)	51 (46)
	over 50 to 100 (2 to 4) incl.	72 (66)	59 (54)
HPS 485W (HPS 70W)	to 100 (4) incl.	78 (71)	66 (60)

Fracture Toughness vs. Historically-Accepted



Fracture Toughness vs. Historically-Accepted

Weld	Plate	Fracture Critical Performance			Non-Fracture Critical Performance		
		Zone I	Zone II	Zone III	Zone I	Zone II	Zone III
ESW-NG	51A	**50%-75%**	**75%-95%**	**>95%**	5%-25%	25%-50%	**50%-75%**
	51B	25%-50%	**75%-95%**	**>95%**	5%-25%	25%-50%	**50%-75%**
	53A	**>95%**	**>95%**	**>95%**	**75%-95%**	**>95%**	**>95%**
	53B	**50%-75%**	**75%-95%**	**>95%**	25%-50%	**50%-75%**	**75%-95%**
	71A	**75%-95%**	**>95%**	**>95%**	25%-50%	**75%-95%**	**>95%**
	71B	**>95%**	**>95%**	**>95%**	**75%-95%**	**>95%**	**>95%**
	73A	**>95%**	**>95%**	**>95%**	**75%-95%**	**>95%**	**>95%**
	73B	25%-50%	**50%-75%**	**75%-95%**	5%-25%	25%-50%	**50%-75%**
S80-10	51A	<5%	5%-25%	5%-25%	<5%	<5%	<5%
	51B	<5%	5%-25%	25%-50%	<5%	<5%	5%-25%
	53A	**50%-75%**	**75%-95%**	**>95%**	5%-25%	25%-50%	**75%-95%**
	53B	5%-25%	5%-25%	25%-50%	<5%	5%-25%	5%-25%
	71A	<5%	5%-25%	25%-50%	<5%	<5%	5%-25%
	71B	<5%	25%-50%	**50%-75%**	5%-25%	5%-25%	25%-50%
	73A	<5%	5%-25%	5%-25%	<5%	<5%	5%-25%
	73B	<5%	<5%	5%-25%	<5%	<5%	5%-25%
S40-30	51A	<5%	<5%	<5%	<5%	<5%	<5%
	51B	<5%	<5%	5%-25%	<5%	<5%	<5%
	53A	5%-25%	25%-50%	**50%-75%**	<5%	5%-25%	25%-50%
	53B	<5%	<5%	5%-25%	<5%	<5%	<5%
	71A	<5%	<5%	<5%	<5%	<5%	<5%
	71B	<5%	<5%	5%-25%	<5%	<5%	<5%
	73A	<5%	<5%	<5%	<5%	<5%	<5%
	73B	<5%	<5%	<5%	<5%	<5%	<5%

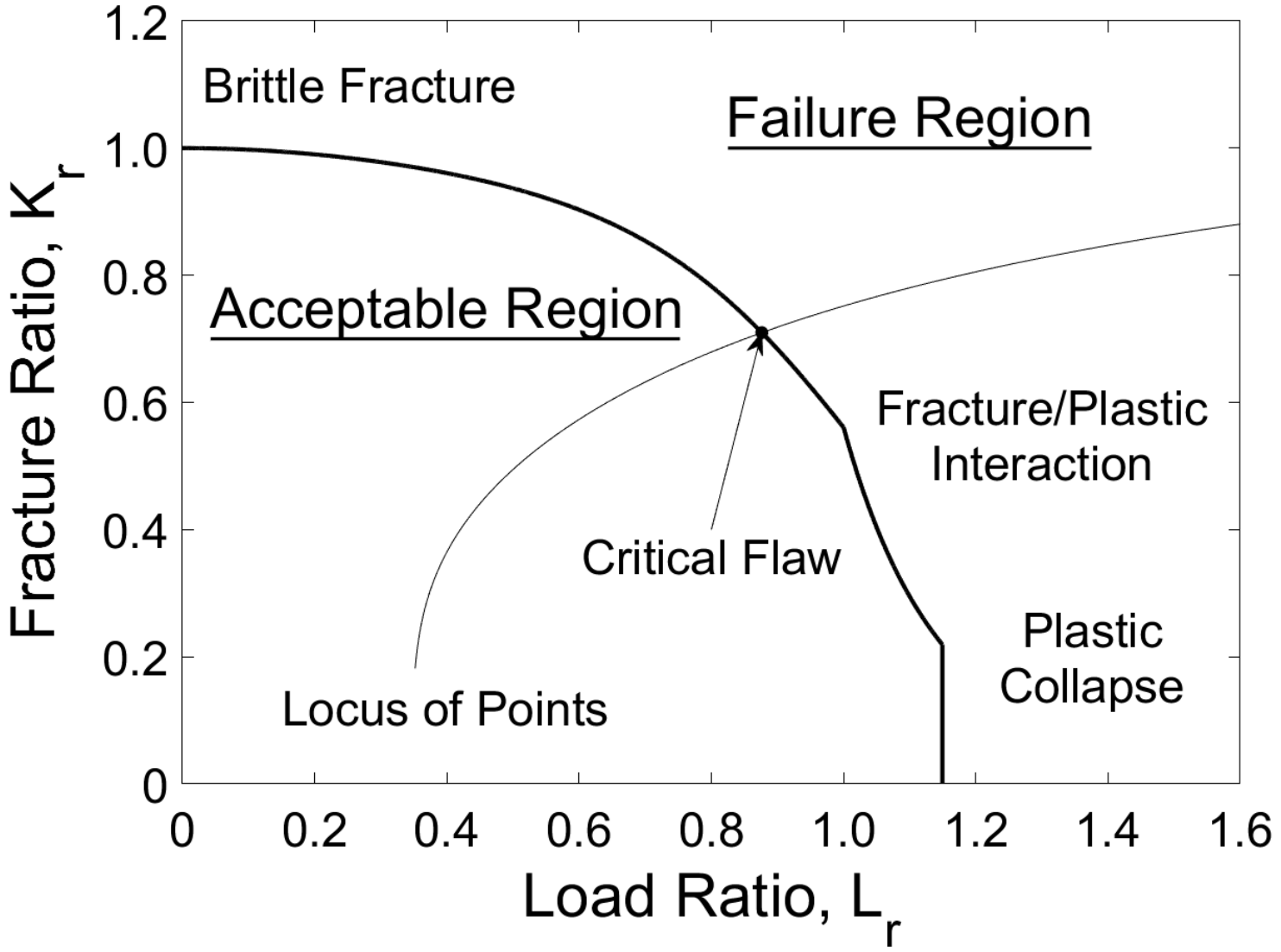
Fracture Toughness vs. Historically-Accepted

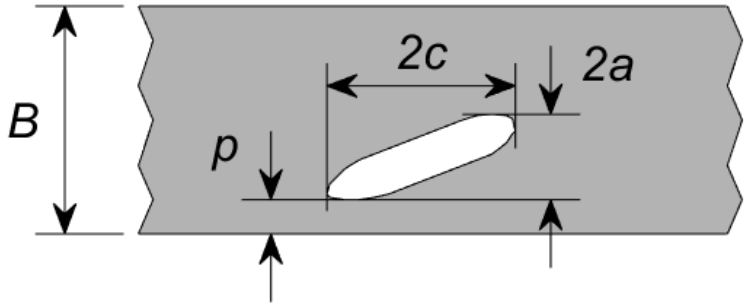
Weld	Plate	Median Fracture Toughness, MPa√m (ksi√in)		
		Zone I: -18°C (0°F)	Zone II: -34°C (-30°F)	Zone III: -51°C (-60°F)
ESW-NG	51A	61 (55)	52 (48)	**46 (42)**
	51B	67 (61)	57 (52)	**50 (45)**
	53A	**49 (45)**	**44 (40)**	**40 (36)**
	53B	67 (61)	**57 (52)**	**50 (45)**
	71A	67 (61)	**57 (52)**	**50 (45)**
	71B	**56 (51)**	**49 (44)**	**44 (40)**
	73A	**53 (48)**	**47 (42)**	**42 (38)**
	73B	88 (80)	72 (66)	**61 (55)**
S10	51A	123 (112)	98 (89)	80 (72)
	51B	108 (98)	87 (79)	72 (65)
	53A	72 (65)	60 (55)	**52 (47)**
	53B	114 (104)	91 (83)	74 (68)
	71A	145 (132)	114 (104)	91 (83)
	71B	108 (99)	87 (79)	72 (65)
	73A	157 (143)	122 (111)	97 (89)
	73B	172 (157)	134 (122)	105 (96)
S30	51A	182 (166)	141 (128)	111 (101)
	51B	149 (136)	117 (106)	93 (85)
	53A	98 (89)	79 (72)	66 (60)
	53B	188 (171)	145 (132)	114 (104)
	71A	248 (226)	189 (172)	146 (133)
	71B	191 (174)	148 (134)	116 (105)
	73A	294 (268)	223 (203)	170 (155)
	73B	240 (218)	183 (166)	141 (129)

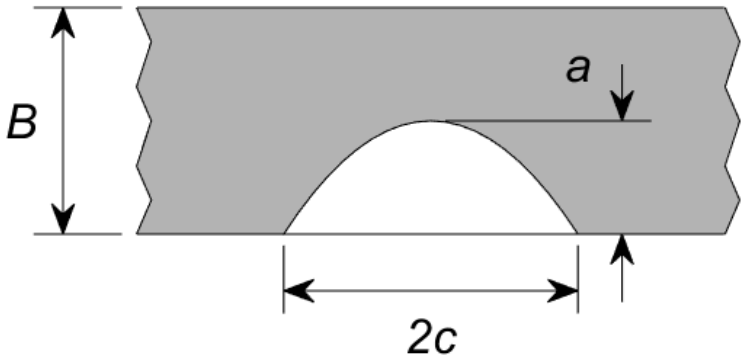
Fracture Toughness vs. Historically-Accepted

Weld	Plate	Average Fracture Toughness, MPa√m (ksi√in)		
		Zone I: -18°C (0°F)	Zone II: -34°C (-30°F)	Zone III: -51°C (-60°F)
ESW-NG	51A	**45 (41)**	-	-
	51B	64 (59)	-	-
	53A	**38 (34)**	**31 (28)**	-
	53B	**39 (36)**	-	-
	71A	**57 (52)**	**40 (36)**	**23 (21)**
	71B	**56 (51)**	-	-
	73A	**37 (34)**	-	-
	73B	**54 (49)**	-	-
S10	51A	123 (112)	90 (82)	69 (63)
	51B	137 (125)	83 (75)	68 (62)
	53A	79 (72)	**55 (51)**	**39 (36)**
	53B	-	102 (93)	69 (62)
	71A	-	**55 (51)**	107 (98)
	71B	126 (114)	70 (64)	**55 (50)**
	73A	-	-	96 (88)
	73B	-	-	123 (112)
S30	51A	-	-	209 (191)
	51B	-	160 (146)	83 (76)
	53A	83 (76)	74 (68)	-
	53B	-	119 (108)	134 (122)
	71A	-	-	179 (163)
	71B	-	142 (129)	120 (110)
	73A	-	-	142 (129)
	73B	-	-	214 (195)

Failure Assessment







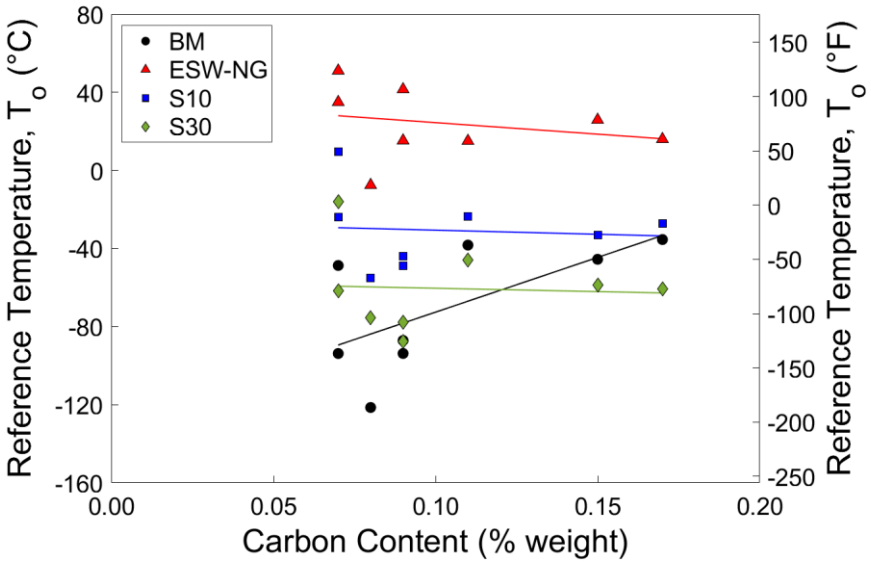
Failure Assessment

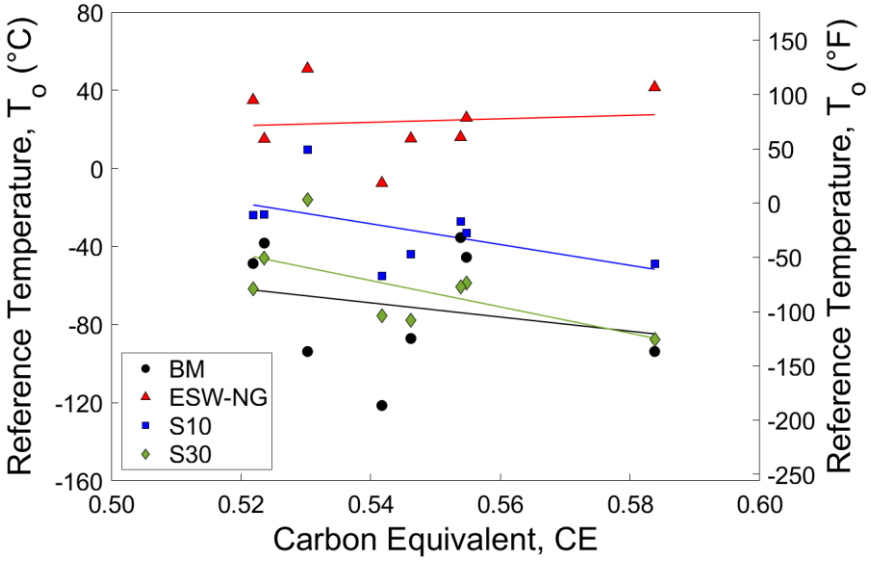
Embedded	Lack of Fusion: $a/2c \approx 0.5$ Slag Inclusion: $a/2c \approx 0.1$
Surface	Undercut: $a/2c \approx 0.1$ Fatigue Crack: $a/2c \approx 0.5$

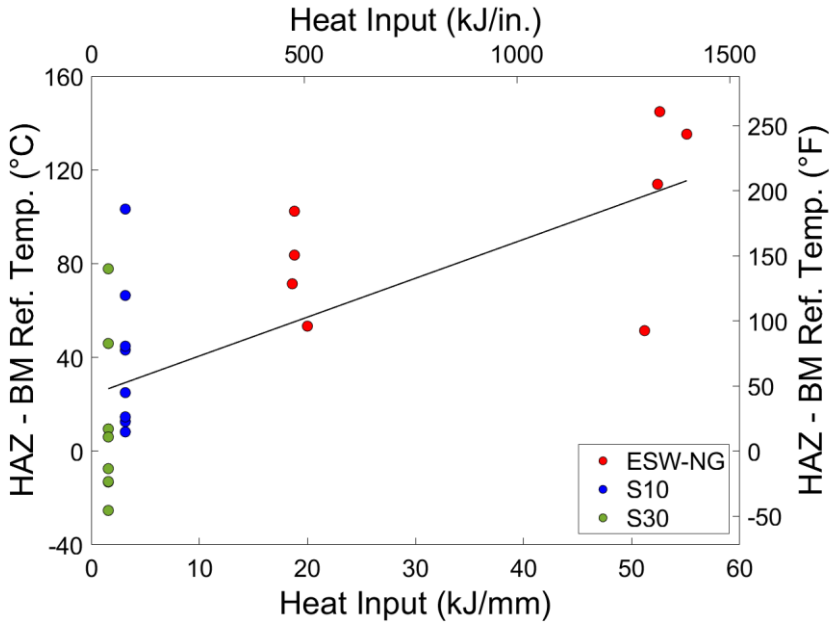
Failure Assessment – Surface Flaw

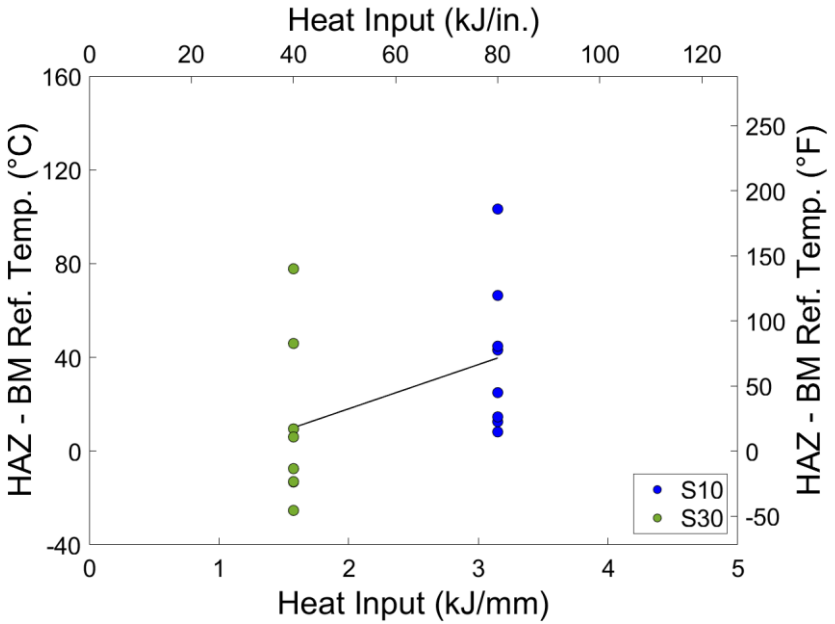
Weld	Thickness mm (in.)	Percent Change in Critical Surface Flaw Length, mm (in.)											
		Grade 345/345W (50/50W)						Grade 485W (70W)					
		Fracture Critical			Non-Fracture Critical			Fracture Critical			Non-Fracture Critical		
		Zone I	Zone II	Zone III	Zone I	Zone II	Zone III	Zone I	Zone II	Zone III	Zone I	Zone II	Zone III
ESW-NG	25 (1)	-7	-22	-36	24	4	-14	-23	-45	-63	0	-29	-52
	51 (2)	-18	-46	-65	72	10	-28	-45	-70	-83	-1	-45	-69
	76 (3)	-43	-66	-79	12	-34	-58	-50	-76	-87	-1	-52	-74
	102 (4)	-46	-70	-82	14	-38	-64	-54	-76	-85	-1	-48	-68
S10	25 (1)	7	-17	-43	44	10	-24	31	-4	-40	67	23	-23
	51 (2)	-2	-47	-71	105	9	-41	62	-20	-61	193	44	-30
	76 (3)	-25	-62	-80	48	-25	-60	97	-8	-57	282	81	-15
	102 (4)	-19	-59	-79	72	-15	-57	149	11	-51	441	141	7
S30	25 (1)	27	18	-2	70	57	30	48	43	26	91	84	62
	51 (2)	92	31	-25	299	169	52	265	159	47	559	366	164
	76 (3)	107	9	-47	311	116	5	613	285	75	1316	658	241
	102 (4)	153	19	-42	434	149	20	1000	394	116	2287	973	369

Predictive Trends

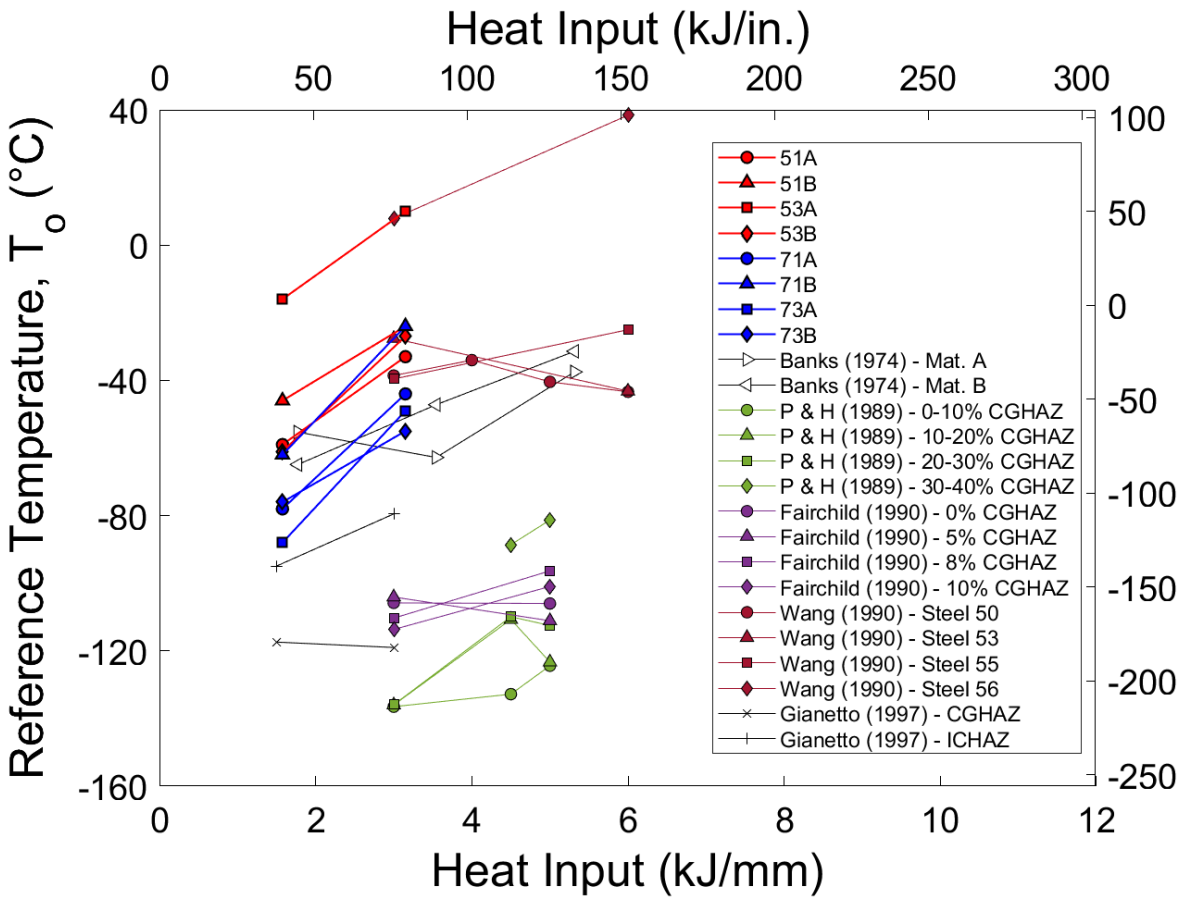


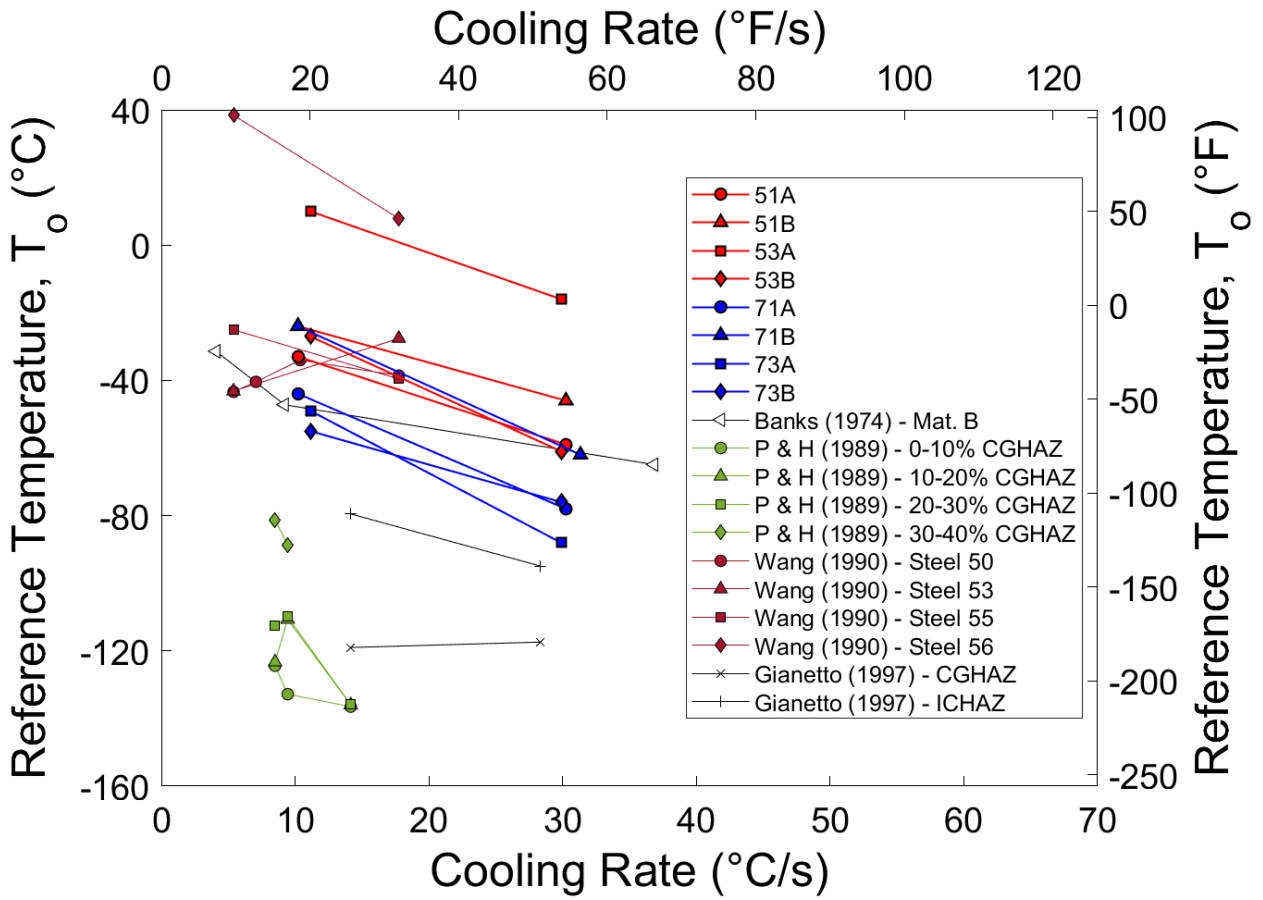




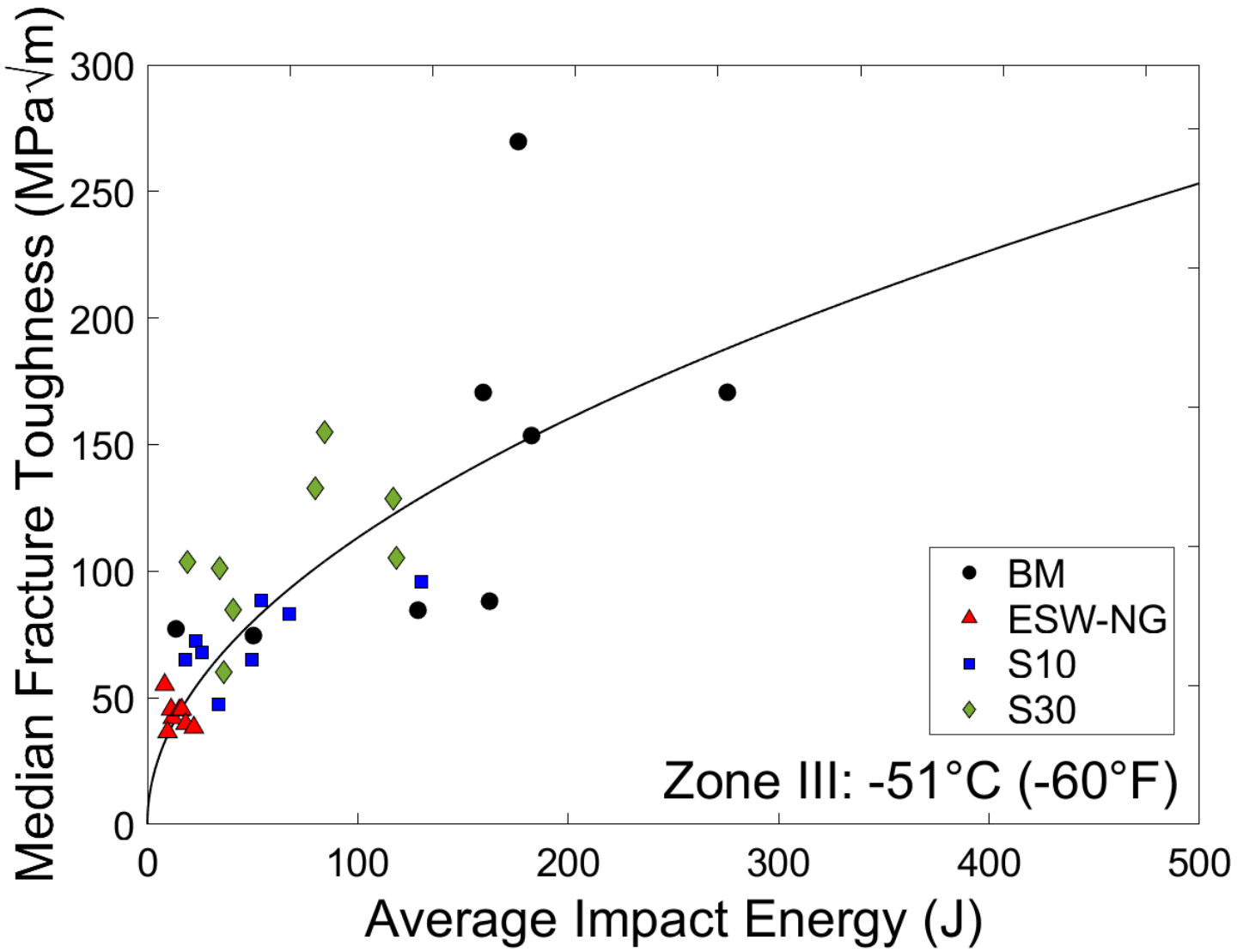


Predictive Trends

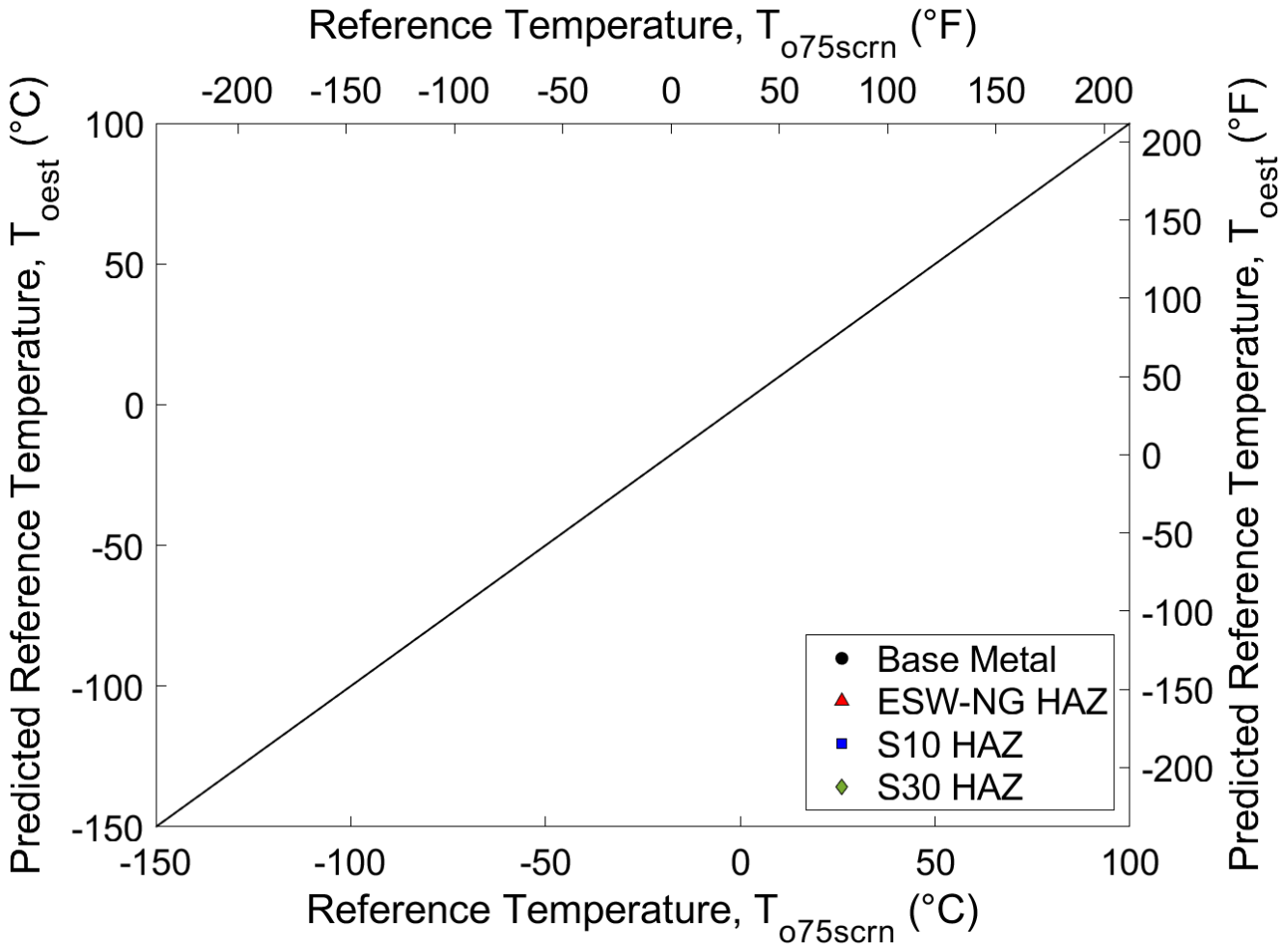




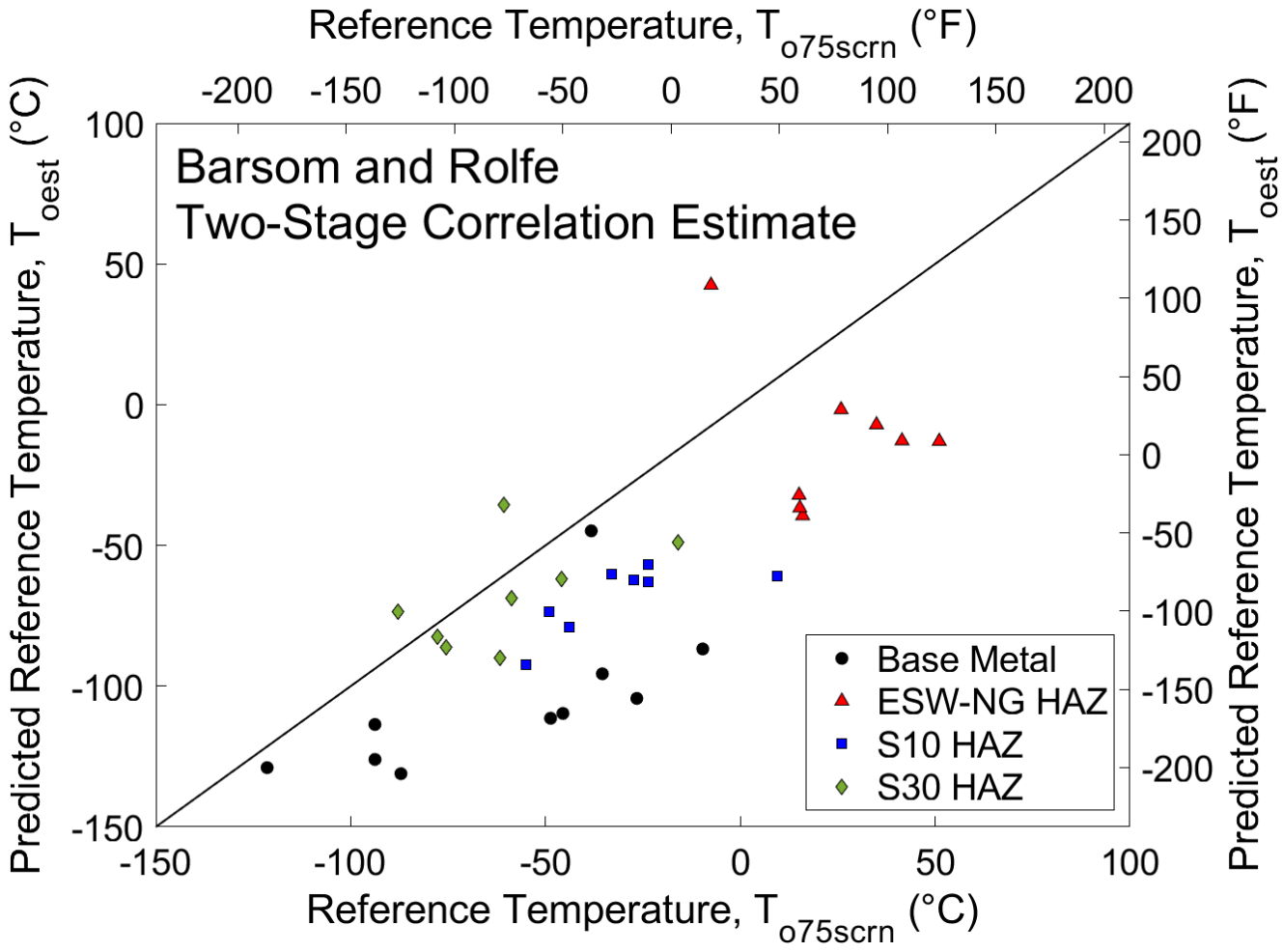
Predictive Trends



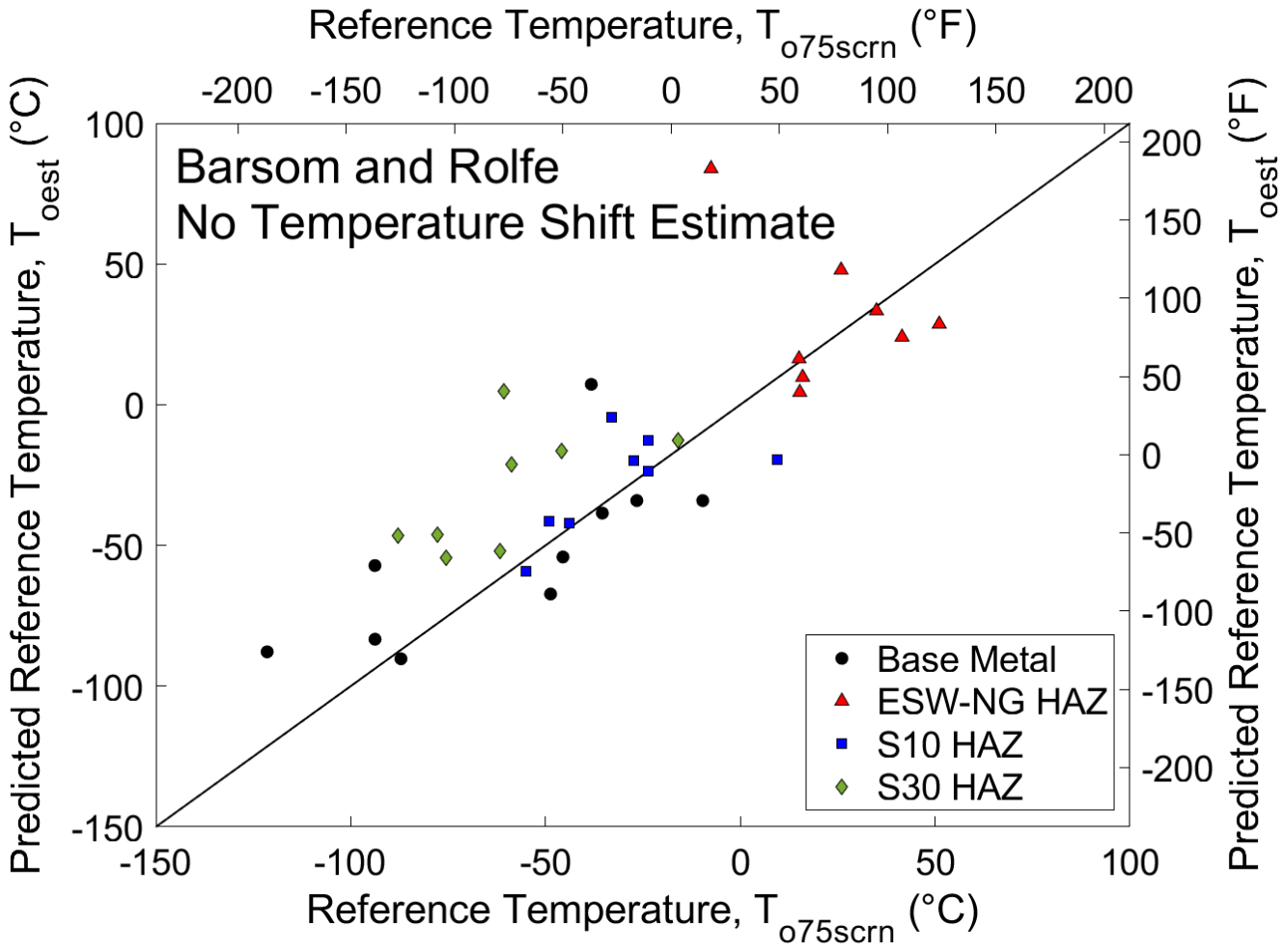
Predictive Trends



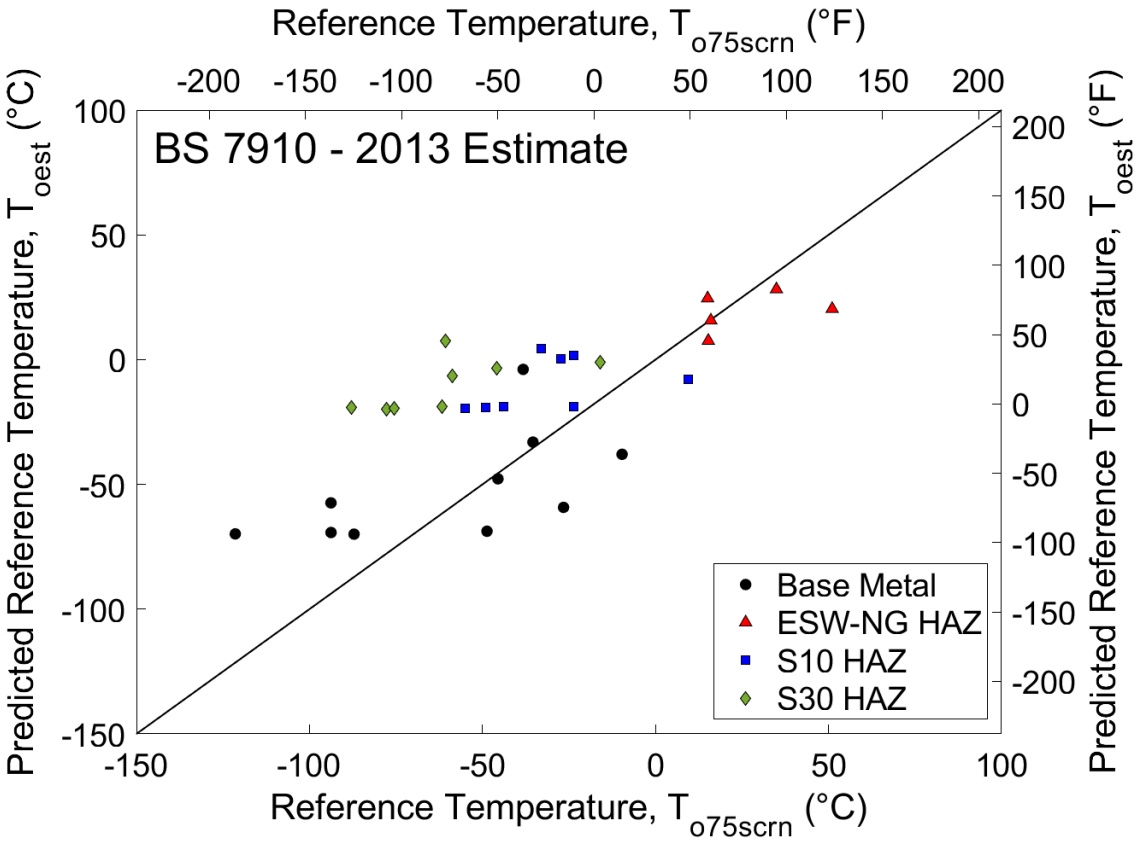
Predictive Trends

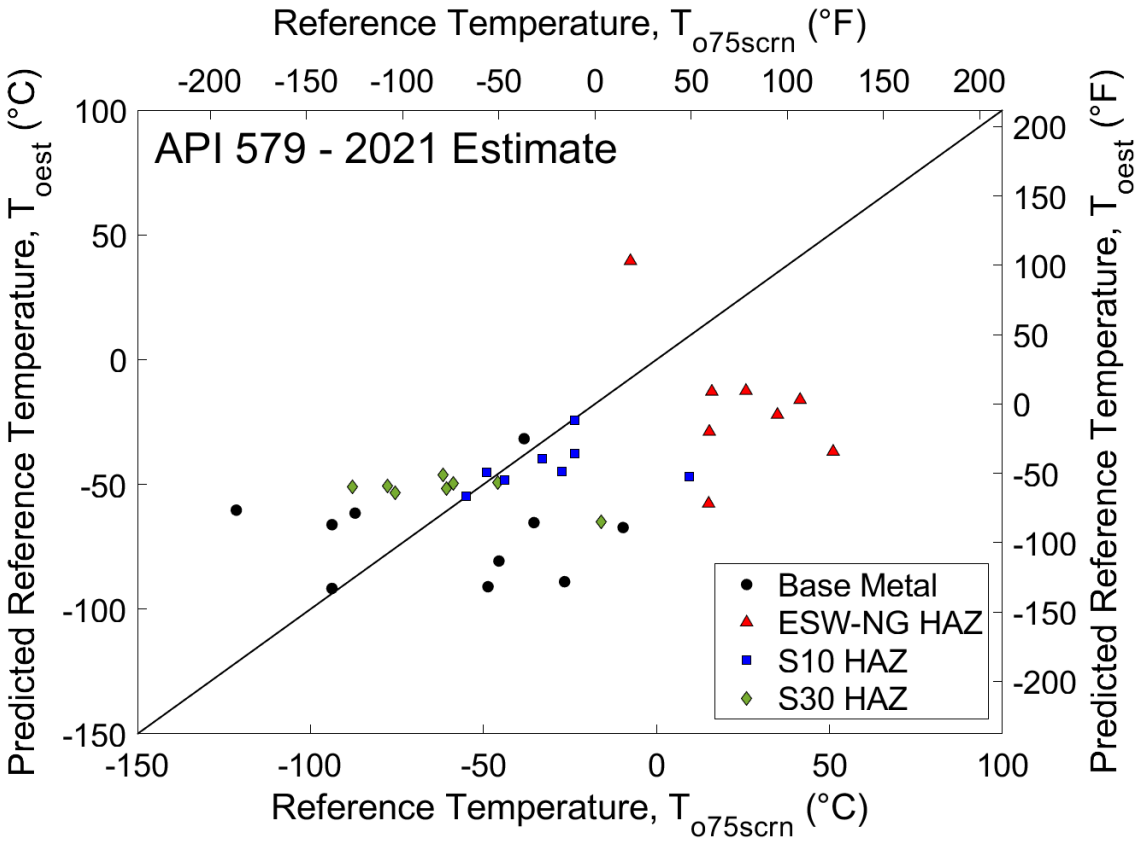


Predictive Trends



Predictive Trends





Conclusions and Recommendations

- SAW HAZ fracture toughness was generally above historically-accepted values for non-FC, Zones I & II
- ESW-NG HAZ well below historically-accepted values
- CVN impact energy inconsistent predictor of fracture toughness
- Predictive trends for HAZ toughness difficult to identify
- Best practices specimen sampling recommendations

Future Work

- More heat inputs, cooling rates, chemistries
- Other weld processes (FCAW, GMAW, SMAW)
- Examine the microstructure of cleavage fracture initiation sites
- Feasibility of other fabrication techniques

NCHRP
Research Report 1056

National
Cooperative
Highway
Research Program

Toughness Requirements for Heat-Affected Zones of Welded Structural Steels for Highway Bridges

NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

Thank You!

William Collins, Ph.D., P.E.
Associate Professor

University of Kansas

Office: 785.864.0672
E-mail: william.collins@ku.edu

Thank You!

William Collins, Ph.D., P.E.
Associate Professor

University of Kansas

Office: 785.864.0672
E-mail: william.collins@ku.edu