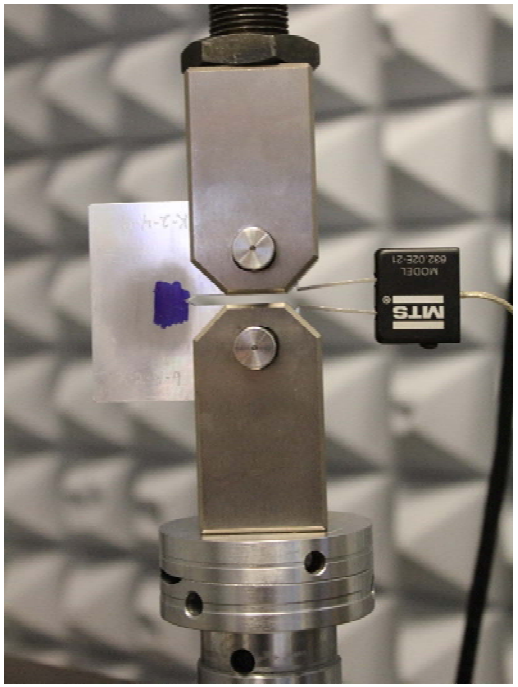
ASTM E399 Standard Development – K_{Isi} Analysis Method

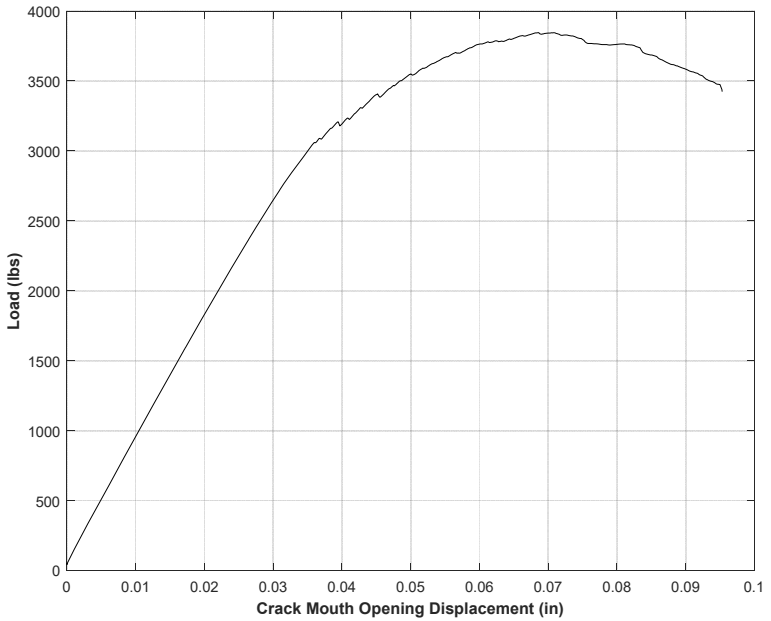
William G. Tilson, Jacobs Space Exploration Group

Background

- The ASTM E399 test method is used to determine the plane-strain fracture toughness, K_{Ic}, for metallic materials.
- The test consists of monotonically loading a precracked test specimen to failure while recording the applied load and the crack mouth opening displacement.



Example Test Setup



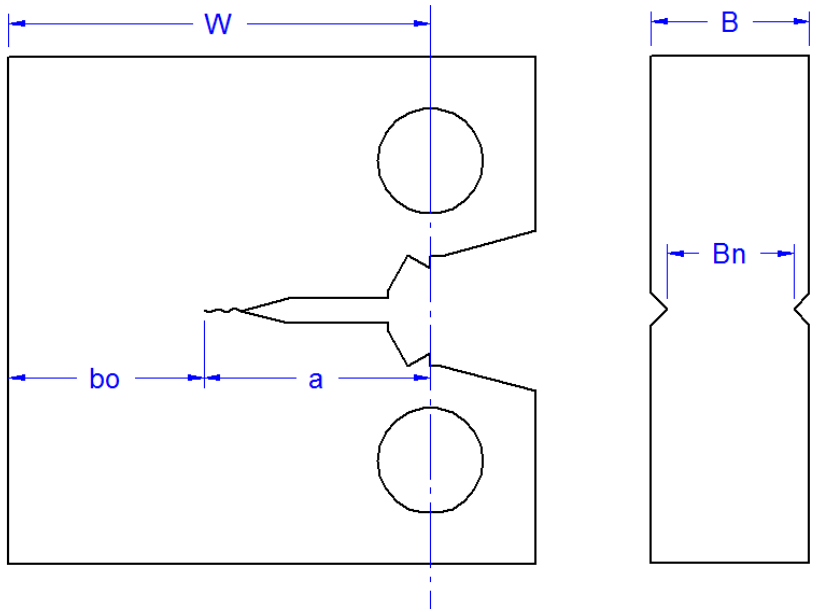
Example Test Record

Background

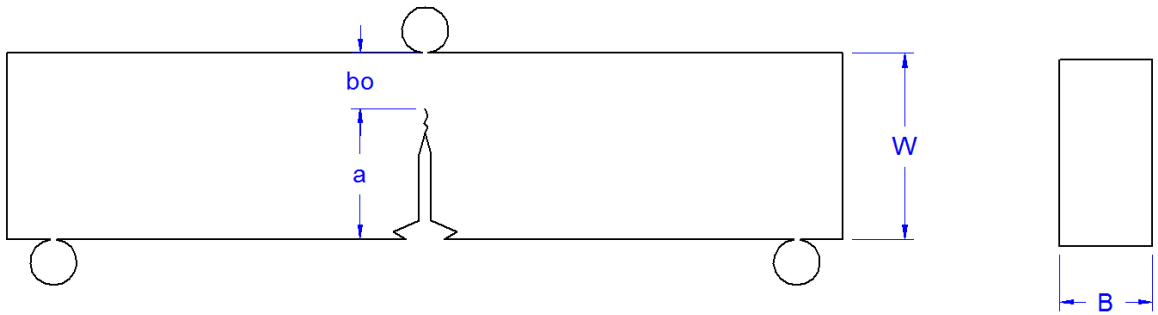
- Several test specimen types are allowable per ASTM E399; two common geometries are the compact tension (C(T)) and the single-edge bend (SE(B)) geometries.

B: thickness
B_n: side groove thickness
W: width
a: crack length
b_o: ligament (W-a)

Compact Tension (C(T))

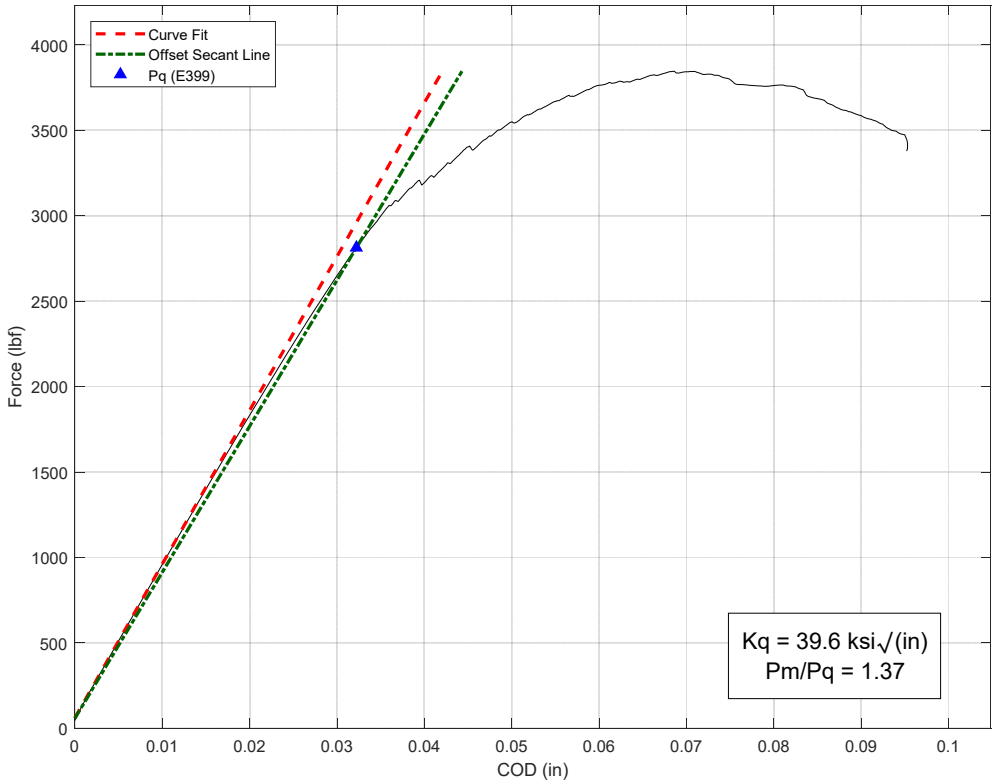


Single Edge Bend (SE(B))



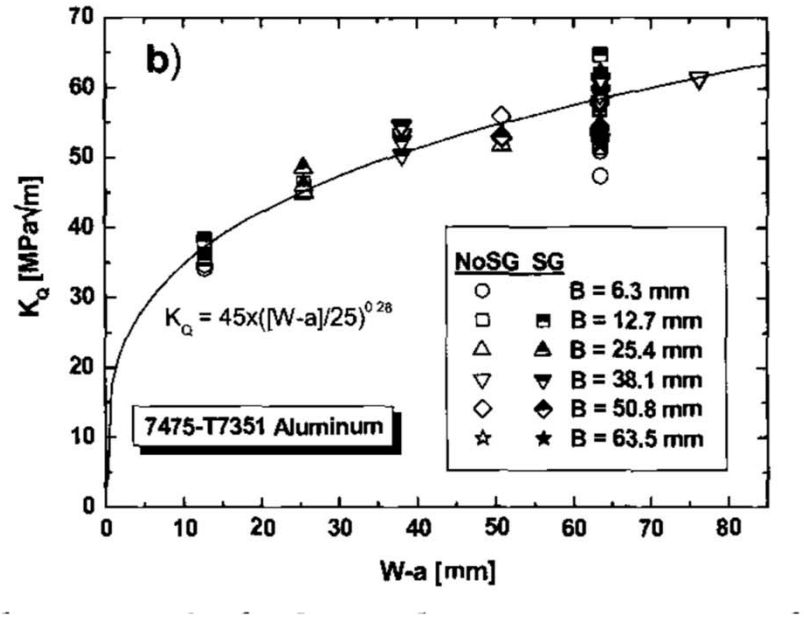
Background

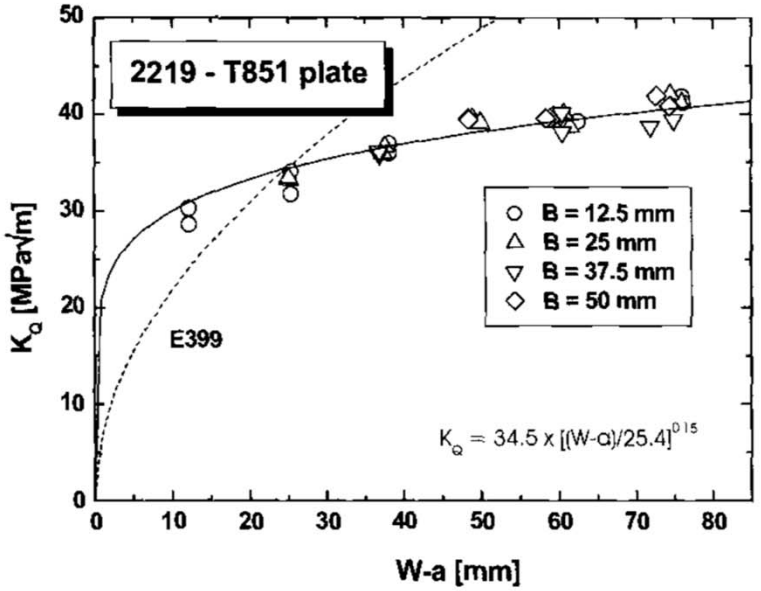
- The test result is an estimate of the plane-strain fracture toughness, K_q, determined by the intercept of the test record with a 95% secant-offset construction line.
- The 95% offset represents crack extension corresponding to ~2% of the original specimen ligament (assuming that all compliance change is the result of crack extension)
- If the test meets certain validity requirements based on specimen size and test behavior, the result is valid, and $K_q = K_{Ic}$



Background

- In 2005, Wallin presented evidence that test results for specimens that exhibit Type I behavior (rising R curve, as shown in the previous example test records) are biased by ligament size.





Wallin, K. R. W. "Critical Assessment of the Standard ASTM E 399," *Journal of ASTM International*, vol. 2, no. 4, pp. 1-21, 2005

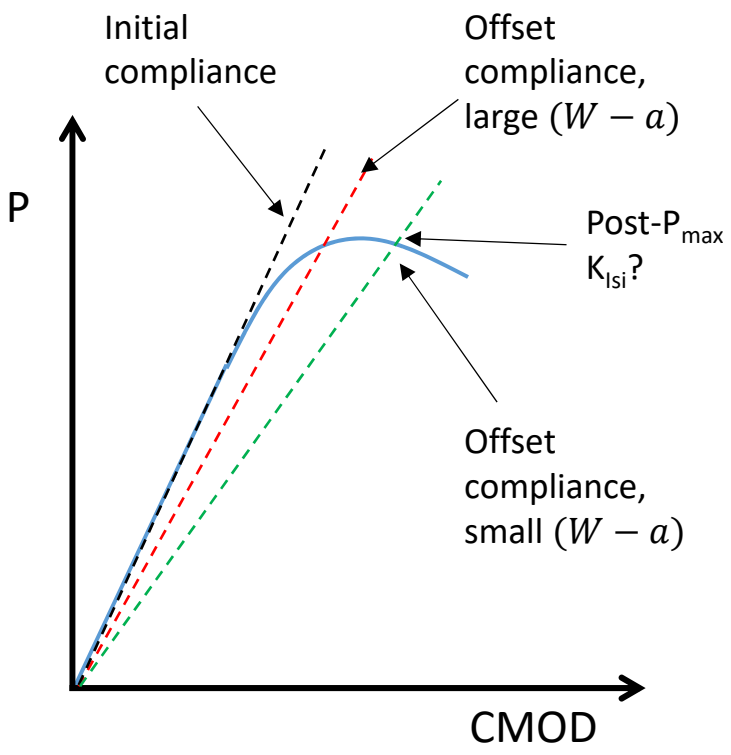
K_{Isi} Analysis Method

- Wallin proposed an alternative analysis method, K_{Isi}, as a size-insensitive fracture toughness parameter, which was later refined by James, et al.
- The offset parameter is a function of ligament size (in mm):

$$\Delta C_{si} = \frac{135}{(W - a)}$$

- Corresponds to a fixed crack extension of 0.5 mm.
- Fixed allowable plastic zone size (in mm).

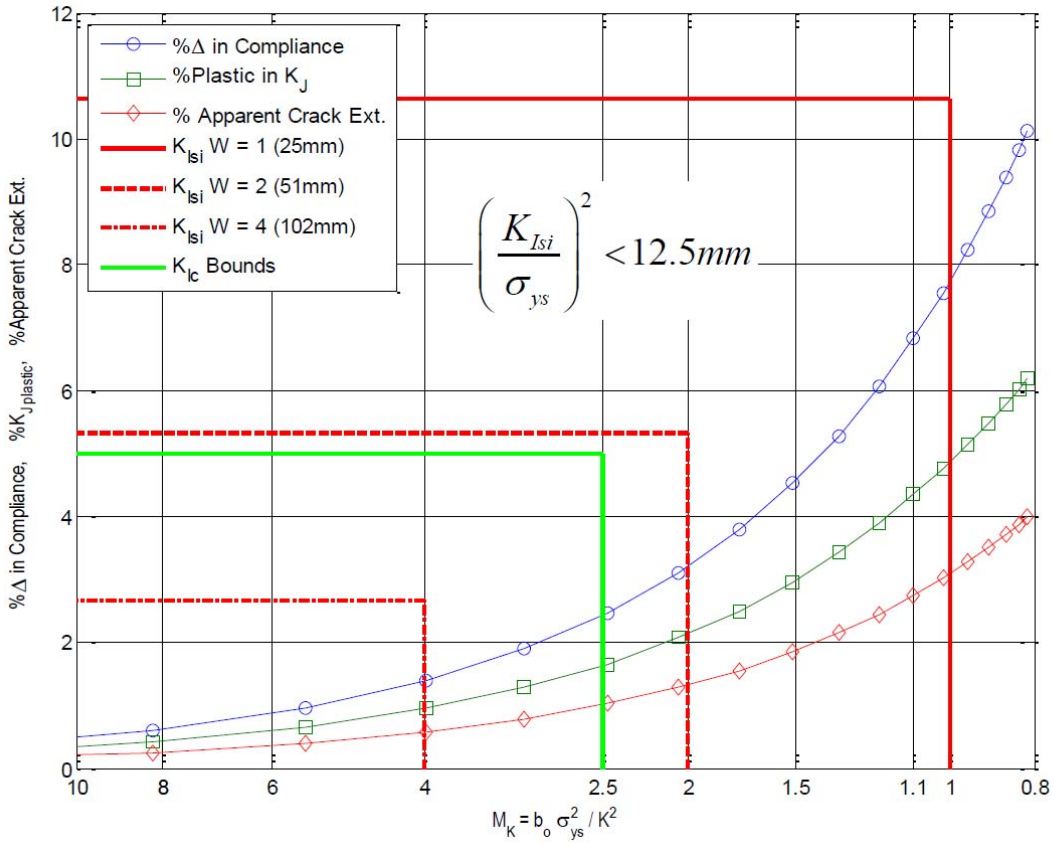
$$\left(\frac{K_{Isi}}{\sigma_{YS}}\right)^2 < 12.5$$



K_{Isi} Analysis Method

- Analysis performed by James, et. al. confirmed that:
  - Limitations on plastic zone size ensure crack extension.
  - Linear-elastic fracture mechanics assumptions are maintained by the alternative approach.
- Define a ligament limit factor, M_K, where

$$M_K = b_0 \left(\frac{\sigma_{ys}}{K}\right)^2$$

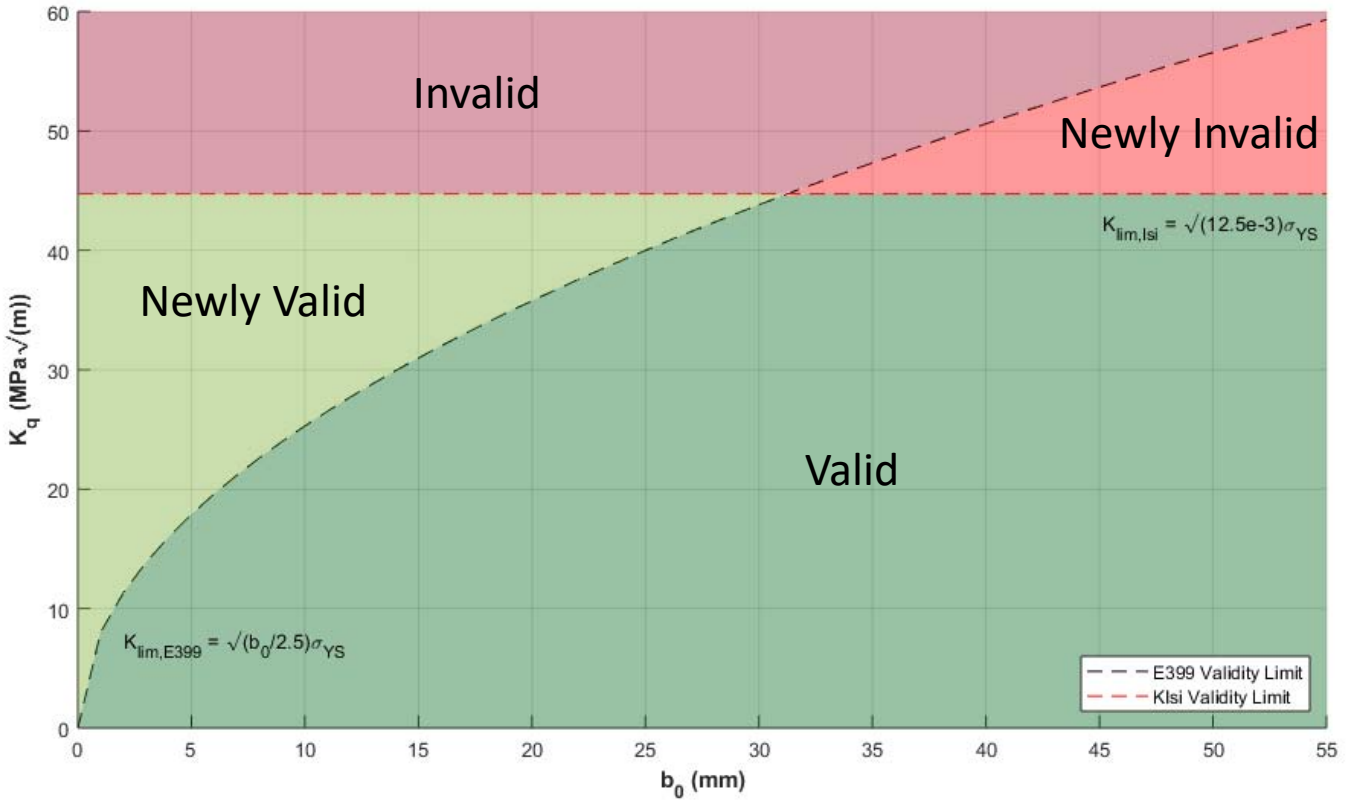


- For E399, M_K=2.5. For K_{Isi}, $M_K = b_0/12.5$ mm

M. James, D. Wells, P. Allen and K. Wallin, "A Review of the Proposed KIsi Offset-Secant Method for Size-Insensitive Linear Elastic Fracture Toughness Evaluation," *17th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics*, 2017.

K_{Isi} Analysis Method

- The new ligament limit factors have the effect of establishing a maximum Kq value for a material based on yield strength.
- This allows valid results for higher toughness materials with small samples, at the cost of invalidating high toughness results from large sample sizes.

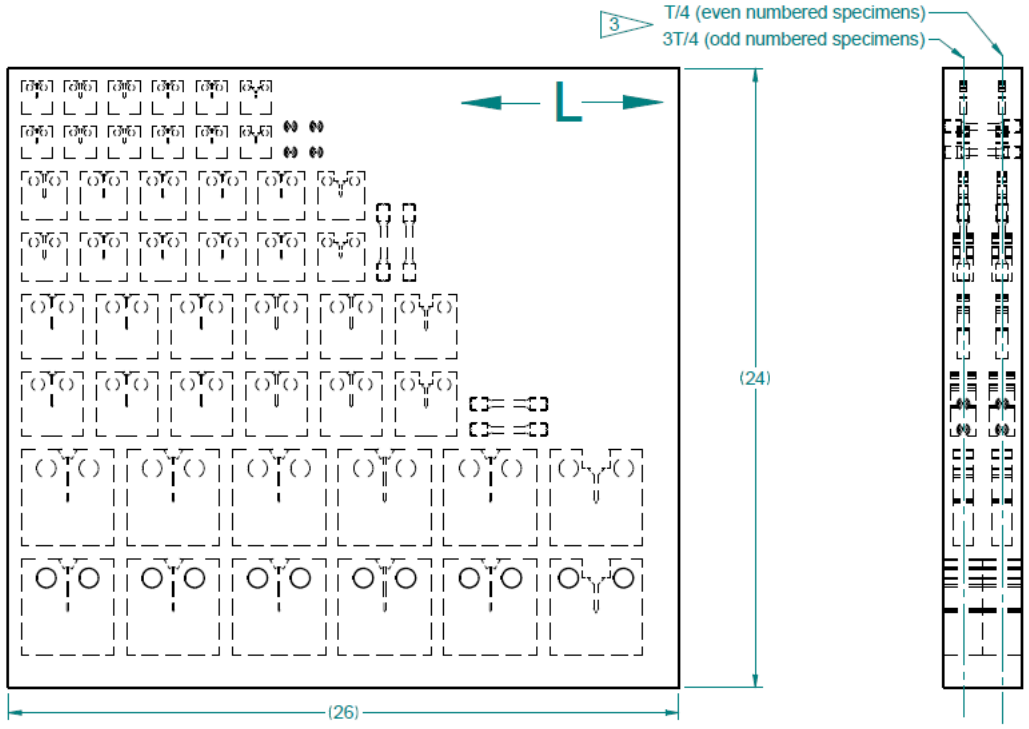


Experimental Validation

- The ongoing study attempts to validate the assumptions of the K_{Isi} analysis method.
  - Are size dependent effects removed when compared to the typical E399 analysis?
  - How accurate is the assumption that the variable secant offset corresponds to 0.5mm crack extension, given plasticity and experimental uncertainties?
  - Do the limits on plastic zone size ensure crack extension?

Test Specimens

- Test specimens were obtained from a plate of 7475-T7351 aluminum.
- Tensile specimens were obtained in the three main directions (L, T, ST).
- Fracture specimens were machined in the L-T direction.
- Details of the cut plan can be found in CP-544.



Test Matrix - Tensile Tests

- Four samples were tested at each orientation (L, T, and ST).
- Average results are shown below.

	Average		
Orientation	**Ultimate Strength (MPa)**	**Yield Strength (MPa)**	**Fracture Elongation (%)**
L	476	401	16.9
T	482	407	13.8
ST	476	390	10.2

Test Matrix – Fracture Tests

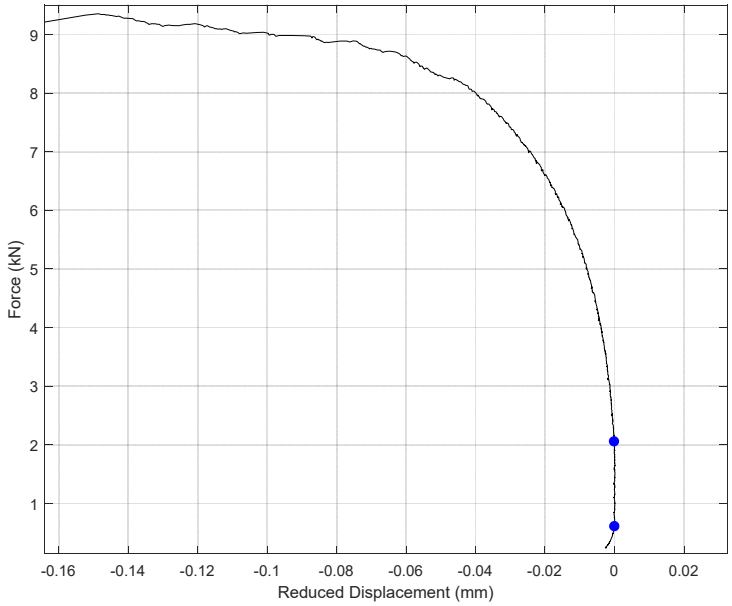
- All specimens have L-T orientation.
- Several spares for each specimen configuration are available for additional testing.

Specimen Dimensions (mm)			Number of Tests				
			E399		E1820	Interrupted	
W	B	W/B	Plane-sided	Side grooved		Plane-sided	Side grooved
25.4	6.35	4	2	1	2	2	1
25.4	12.7	2	2	1	2	2	1
38.1	9.525	4	2	1	2	2	1
38.1	19.05	2	2	1	2	2	1
50.8	12.7	4	2	1	2	2	1
50.8	25.4	2	2	1	2	2	1
76.2	19.05	4	2	1	2	2	1
76.2	38.1	2	2	1	2	2	1

- All currently planned testing is completed.
- Spare samples are available for further tests.

Slope Fitting

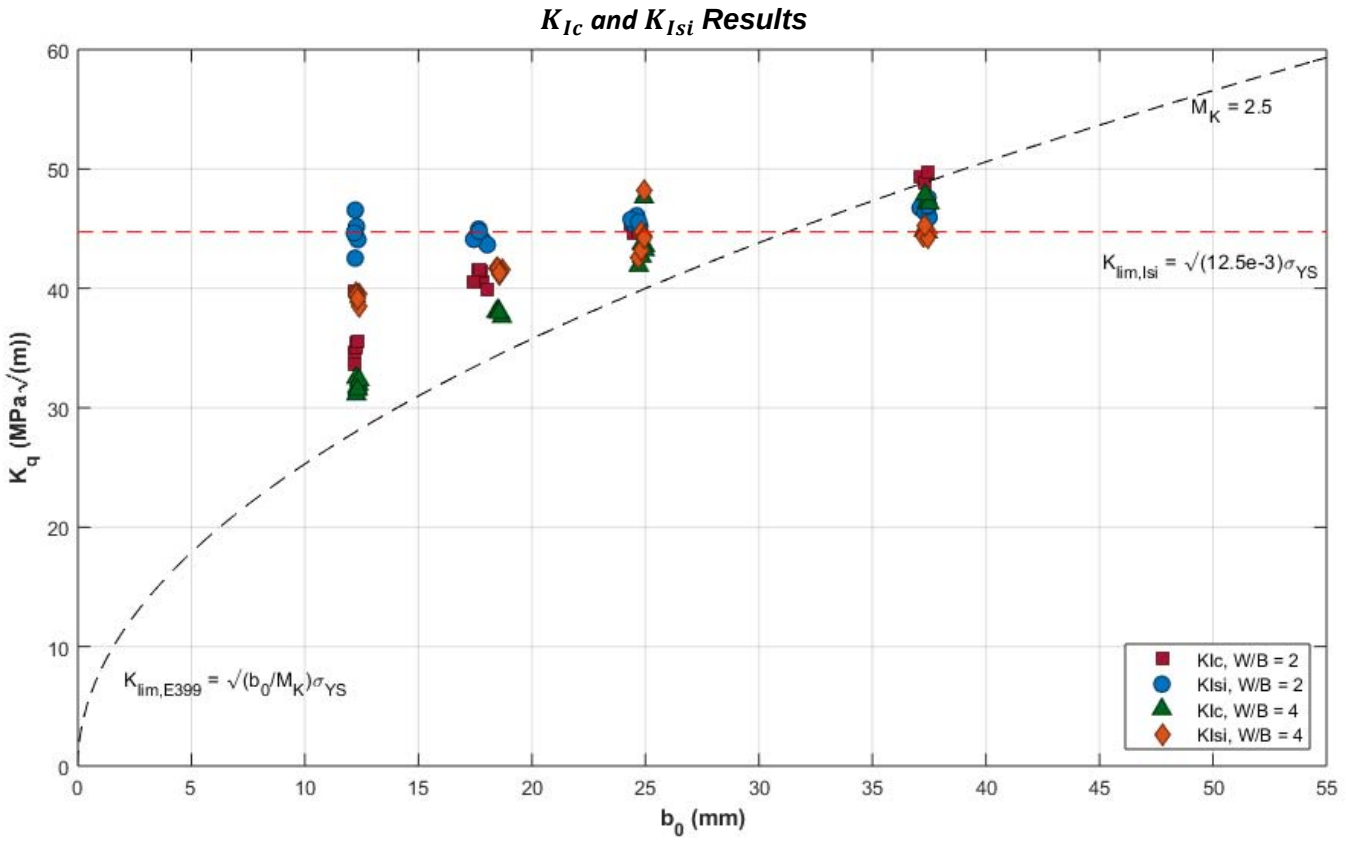
- Slope determination for the purposes of determining the K_{Ic} and K_{Isi} points is done by using the Slope Determination through Analysis of Residuals (SDAR) method, developed by Graham and Adler.
- The SDAR algorithm provides an objective and repeatable method for slope determination.
- The response of this alloy is such that the initial linear region is small; results are sensitive to changes in fit.



S. M. Graham and M. A. Adler, “Determining the Slope and Quality of Fit for the Linear Part of a Test Record," *Journal of Testing and Evaluation, Vol. 39, No. 2*, 2011.

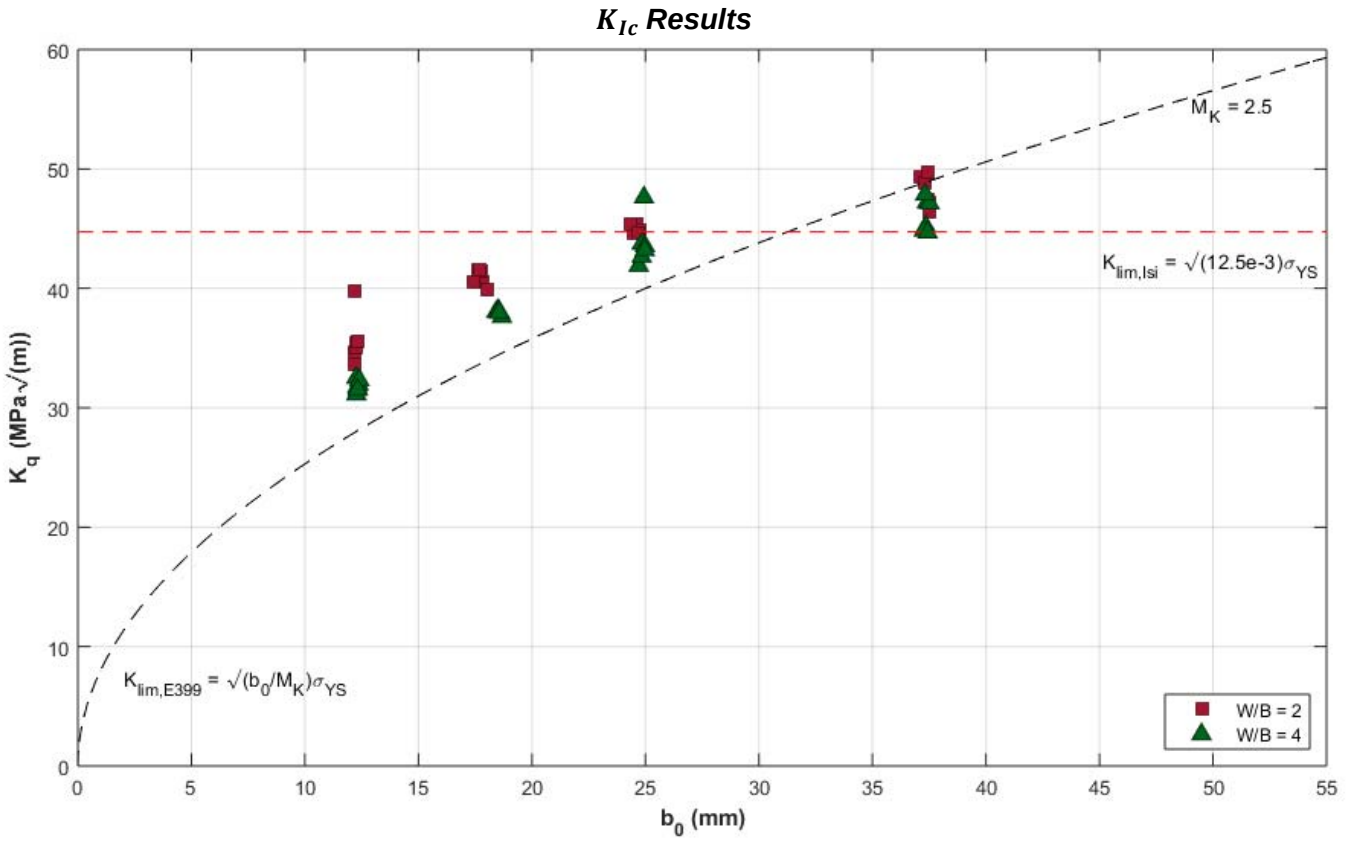
K Results

- In general, the K_{Isi} results are more consistent than the E399 K_{Ic} results. Data shown includes results from interrupted tests, if applicable.
- W/B = 2 tests tend to exhibit slightly higher K_q values than W/B = 4 tests.



K Results

- The E399 K_{Ic} results show the greatest dependence on ligament size. Results are lower than K_{Isi} results at short b_0 and higher than K_{Isi} results at longer b_0. Only the W = 76.2 mm specimens are valid per the ligament requirement.



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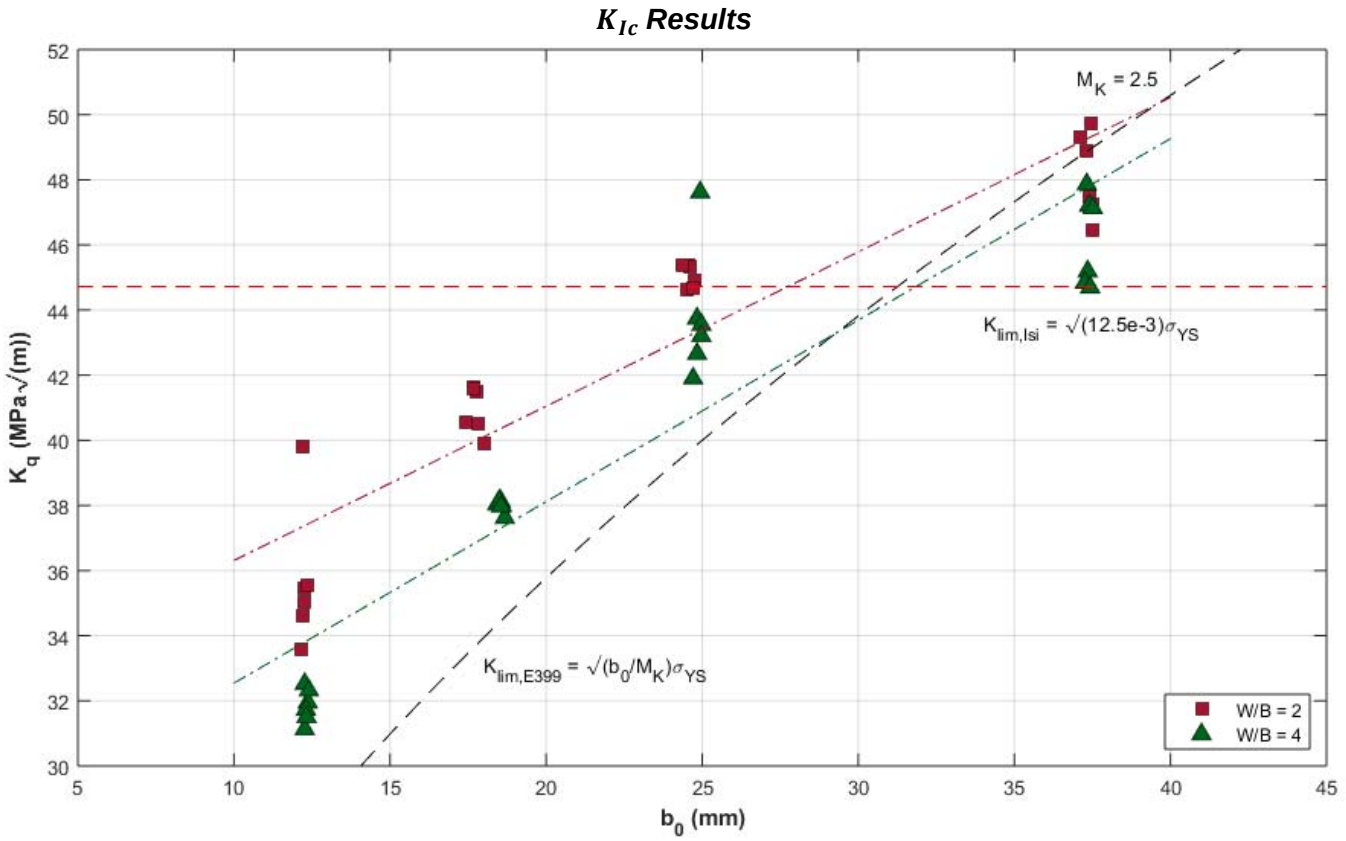
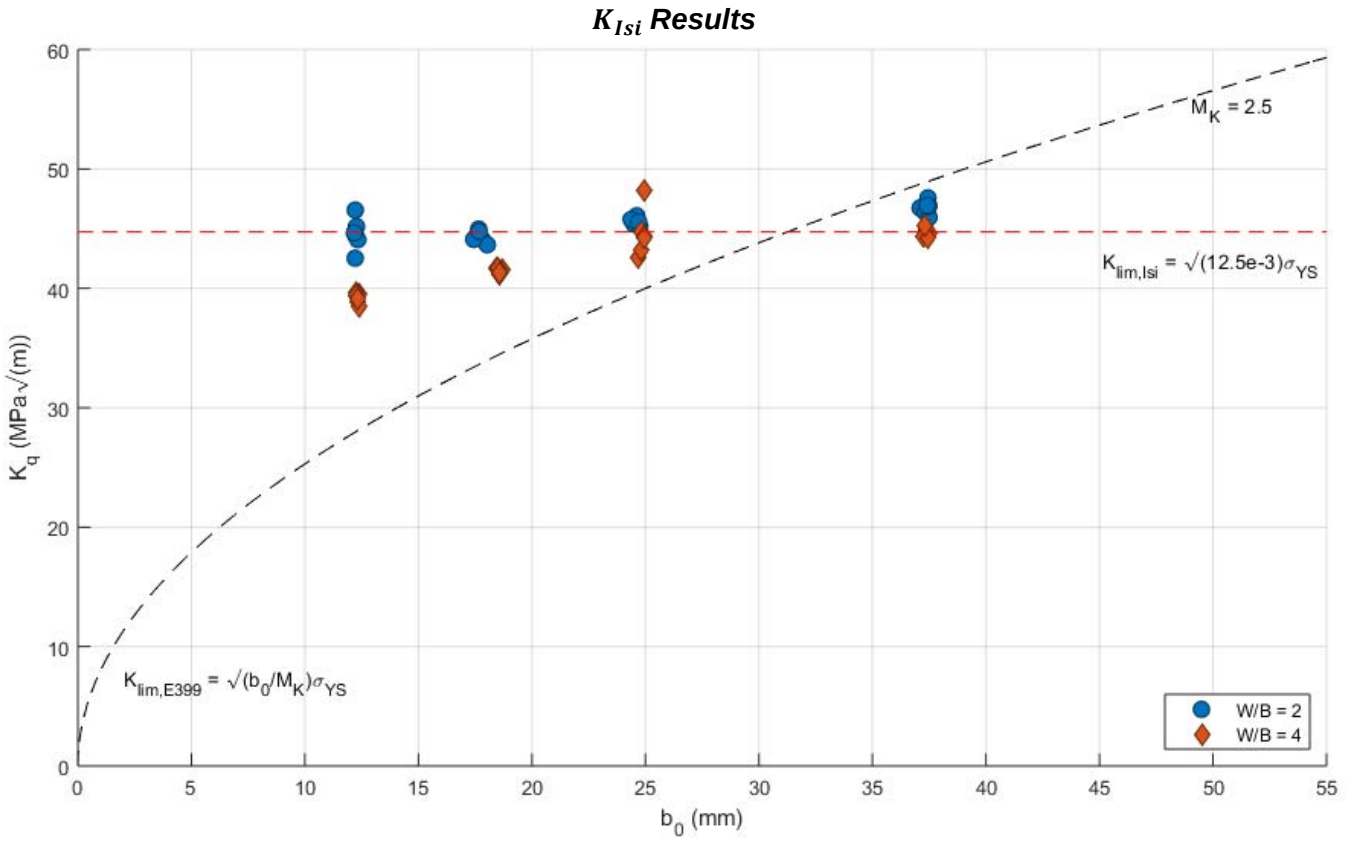
- Linear fits are shown.



K Results

- The K_{Isi} results show reduced dependence on ligament size. Results tend to vary across the ligament validity line for K_{Isi}, with specimens with W/B = 4 falling valid more often.



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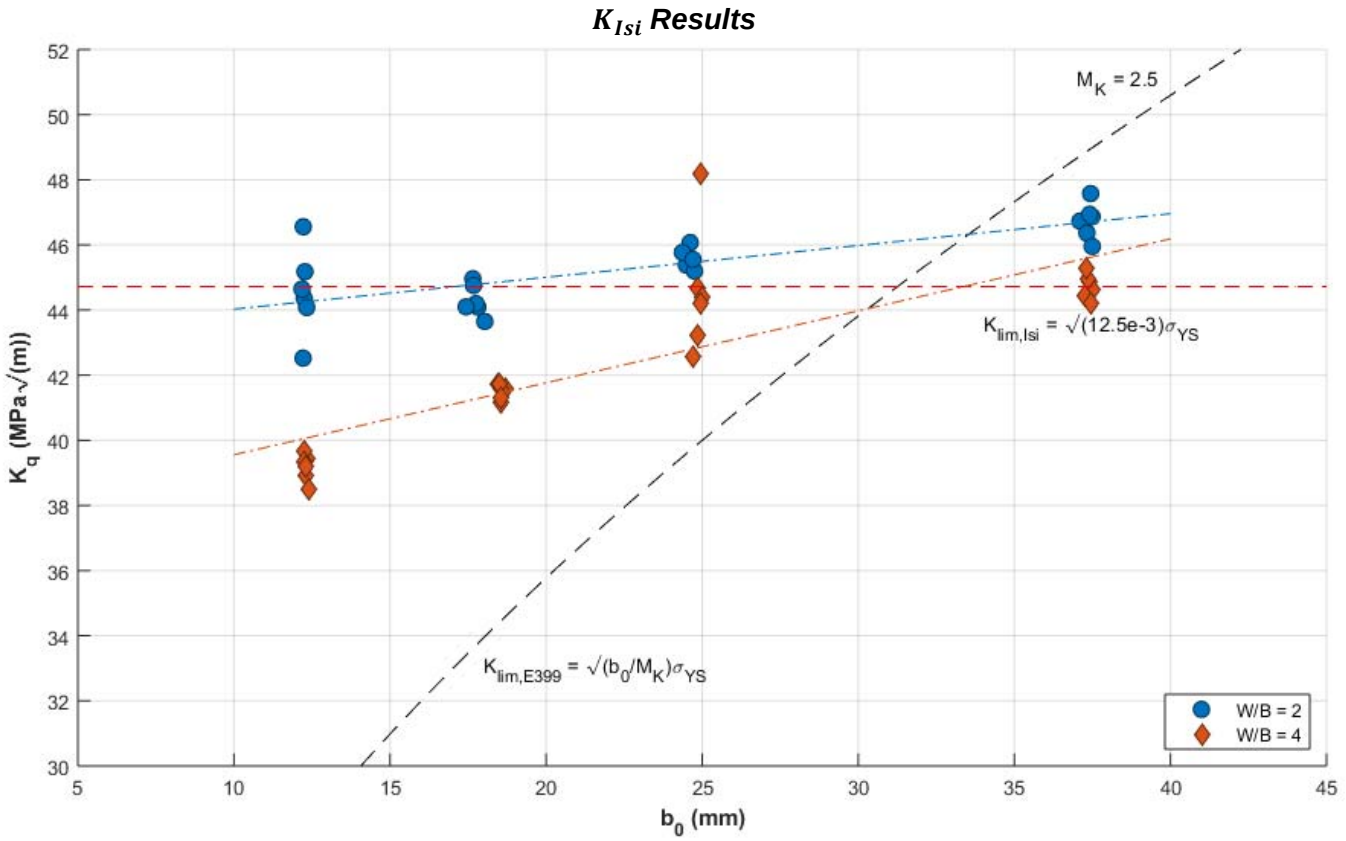
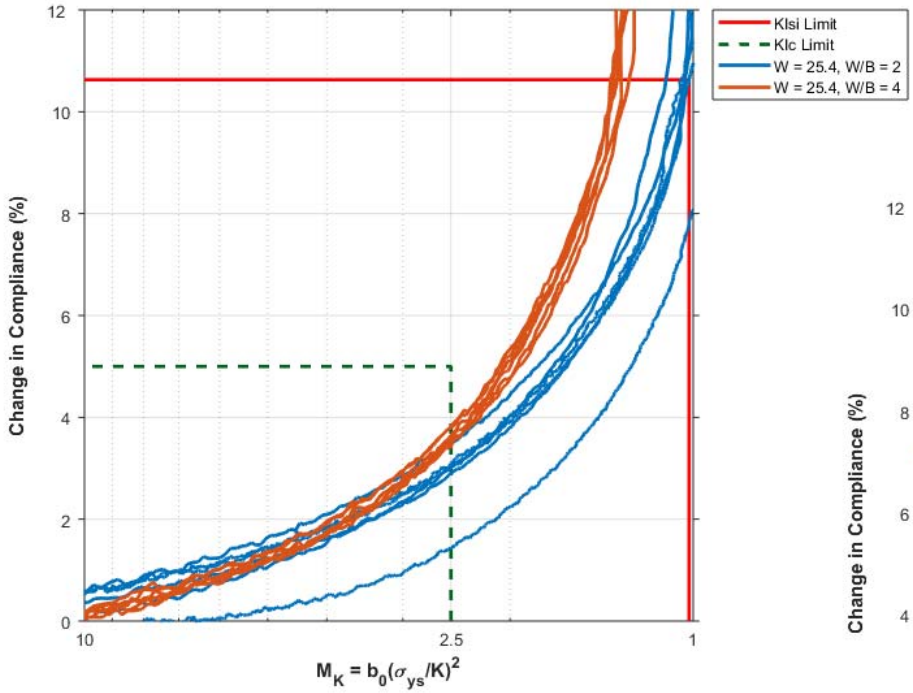
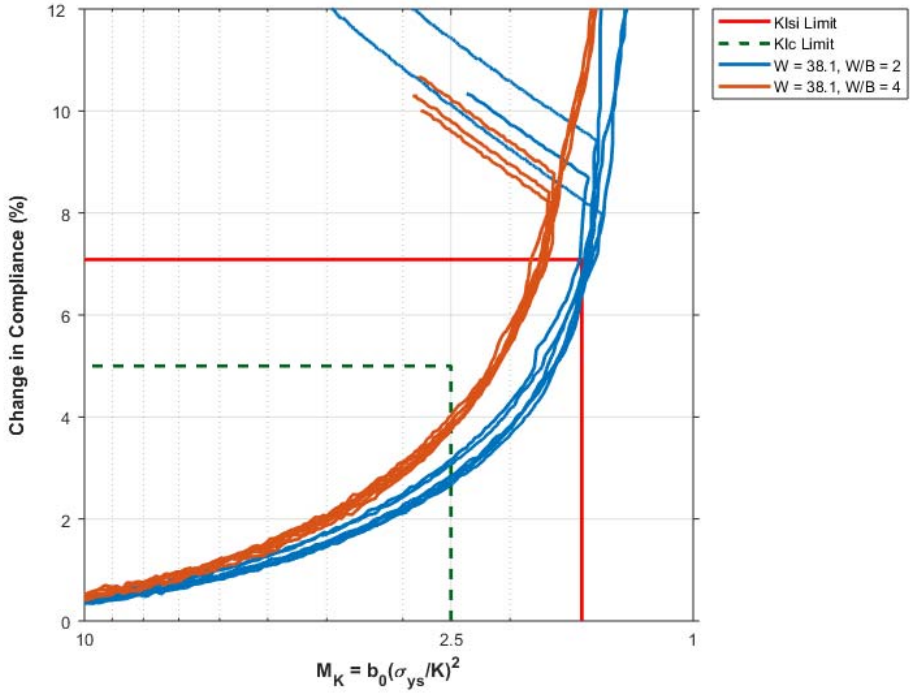


Plasticity Limits

- To be valid, the curve must cross the change in compliance point (5% for K_{Ic}, or based on ligament length, for K_{Isi}) before crossing the M_K limit (2.5 for K_{Ic}, or $b_0/12.5$ for K_{Isi}).
- W/B = 4 specimens consistently pass the criteria; W/B = 2 specimens vary between valid and invalid.





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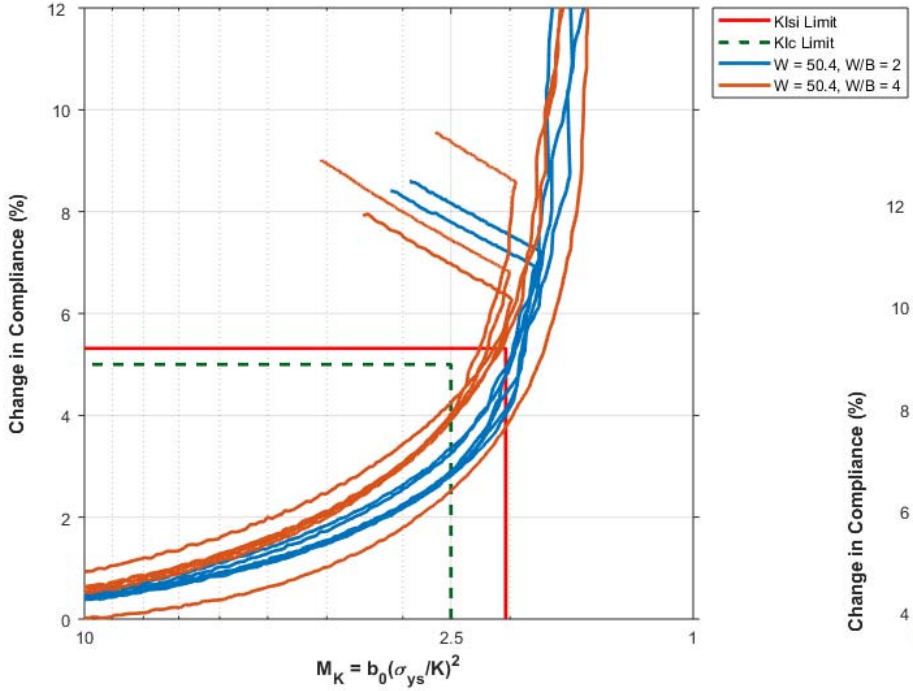
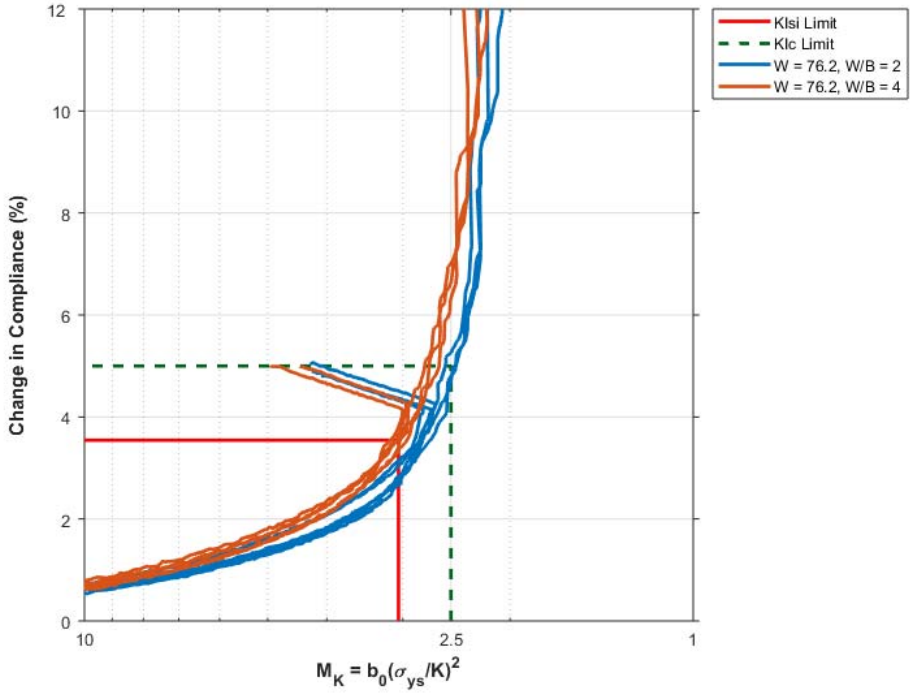
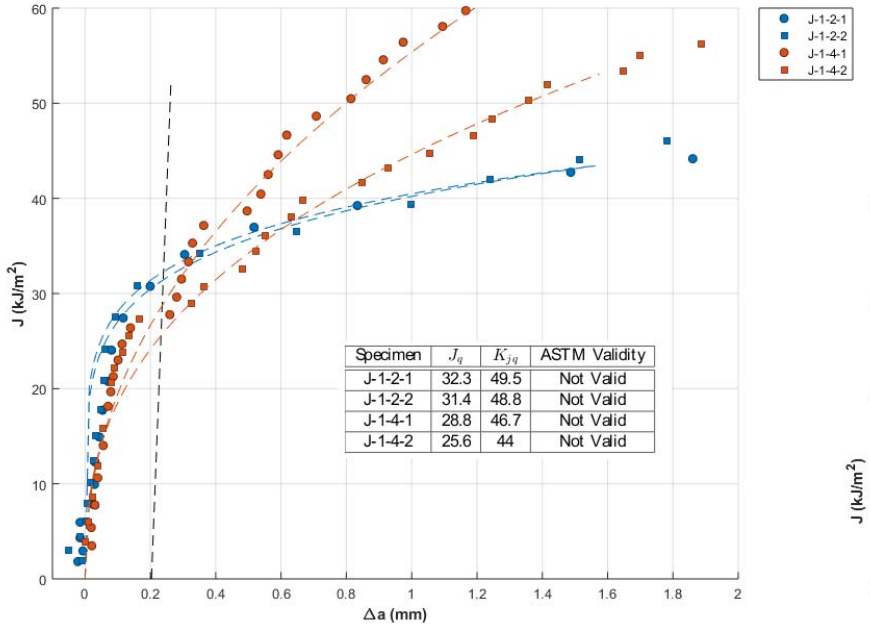


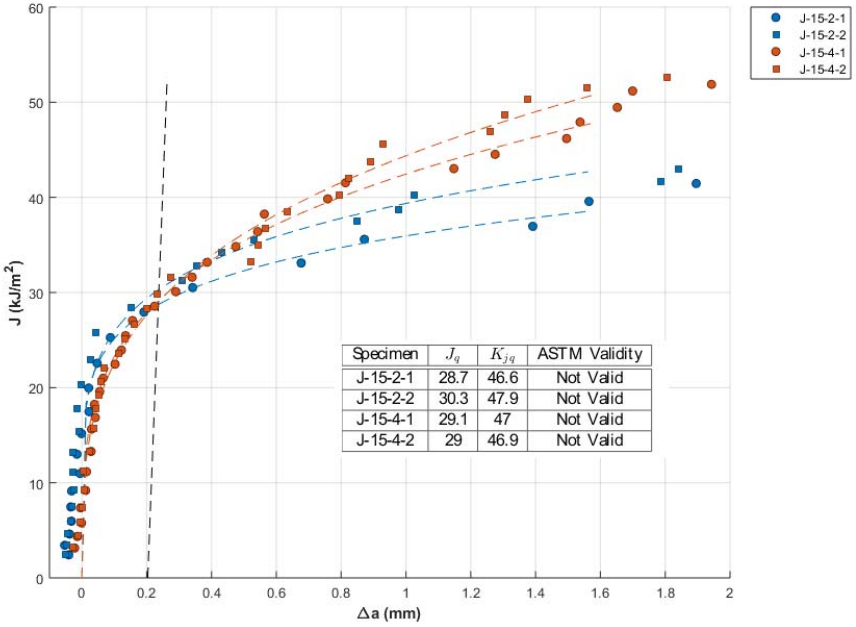


Elastic-Plastic Results

- Specimens with W = 25.4 mm and W/B = 4 show noticeably steeper tearing moduli than specimens with W/B = 2.
- All tests are invalid per ASTM E1820, predominantly due to curvature of final crack fronts.



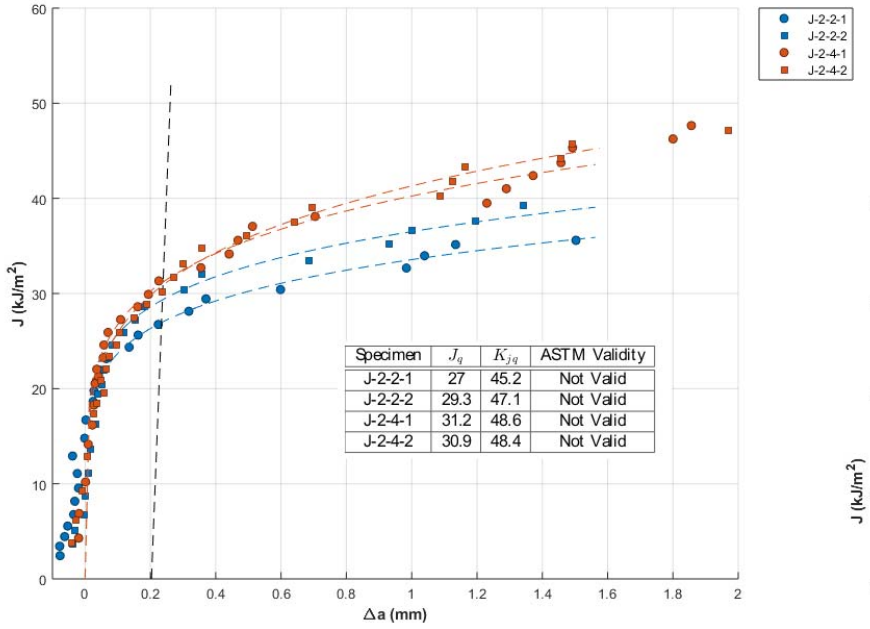
Specimen	J_q	K_{Jq}	ASTM Validity
J-1-2-1	32.3	49.5	Not Valid
J-1-2-2	31.4	48.8	Not Valid
J-1-4-1	28.8	46.7	Not Valid
J-1-4-2	25.6	44	Not Valid



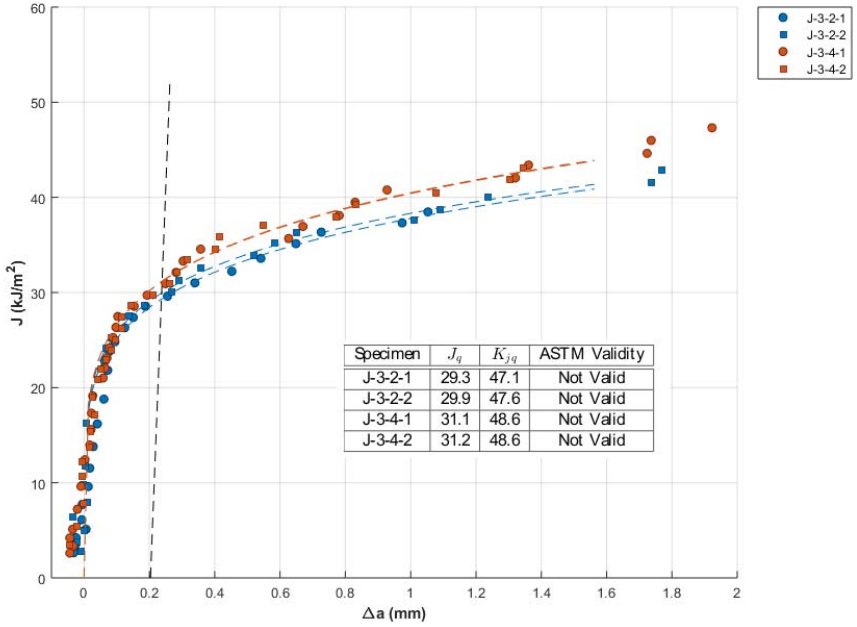
Specimen	J_q	K_{Jq}	ASTM Validity
J-15-2-1	28.7	46.6	Not Valid
J-15-2-2	30.3	47.9	Not Valid
J-15-4-1	29.1	47	Not Valid
J-15-4-2	29	46.9	Not Valid

Elastic-Plastic Results

- Specimens with W = 50.8 mm and 78.2 mm show similar tearing behavior regardless of W/B ratio. Specimens with W/B = 4 exhibit slightly higher J_q values.
- All tests are invalid per ASTM E1820, predominantly due to curvature of final crack fronts.



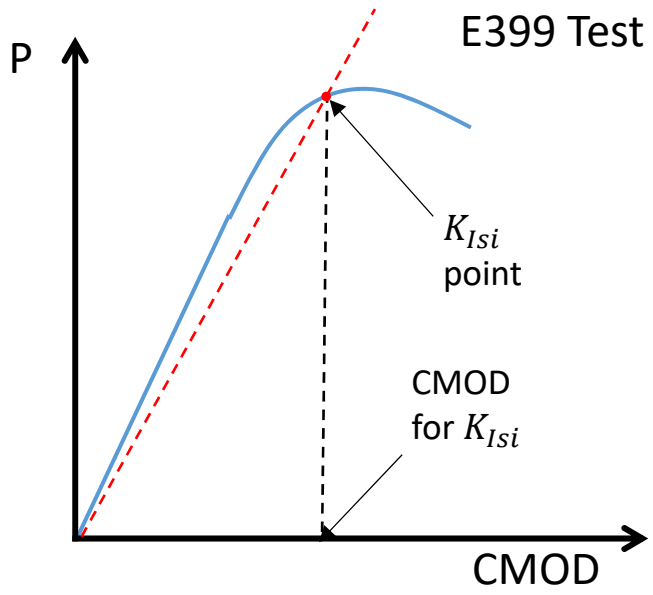
Specimen	J_q	K_{Jq}	ASTM Validity
J-2-2-1	27	45.2	Not Valid
J-2-2-2	29.3	47.1	Not Valid
J-2-4-1	31.2	48.6	Not Valid
J-2-4-2	30.9	48.4	Not Valid

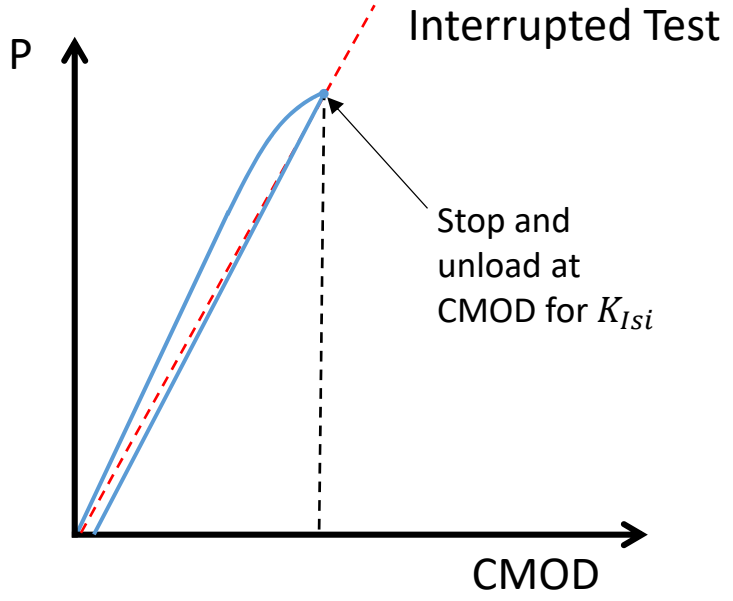


Specimen	J_q	K_{Jq}	ASTM Validity
J-3-2-1	29.3	47.1	Not Valid
J-3-2-2	29.9	47.6	Not Valid
J-3-4-1	31.1	48.6	Not Valid
J-3-4-2	31.2	48.6	Not Valid

Interrupted Tests

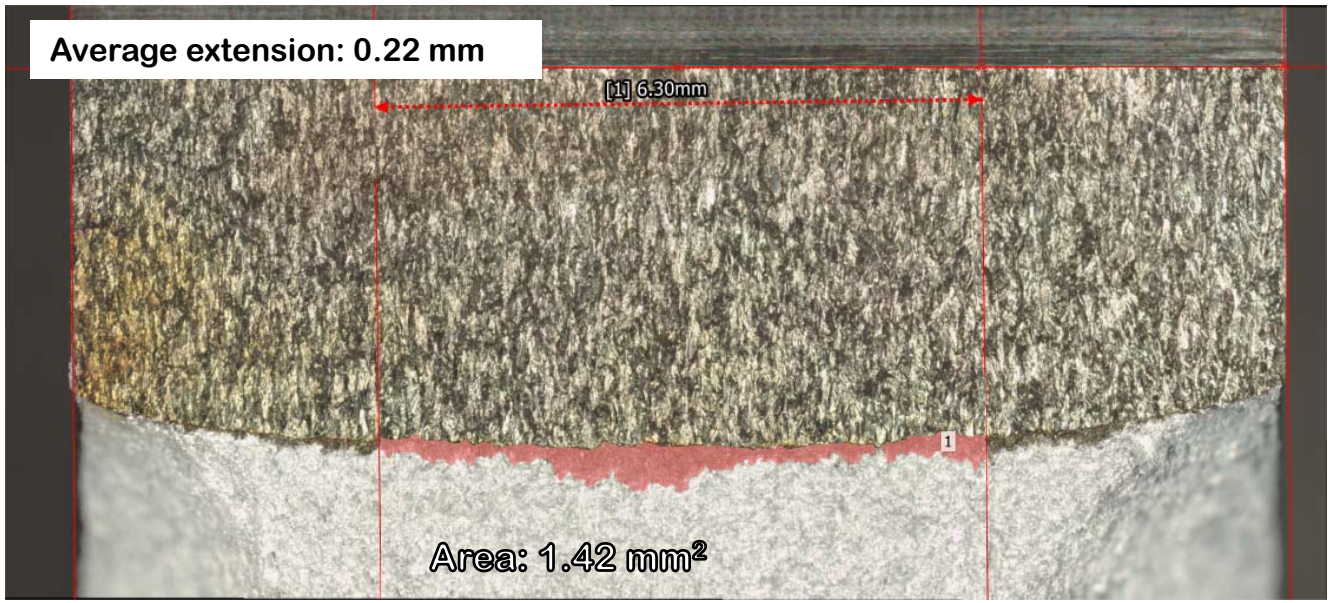
- The goal is to validate that the K_{Isi} point corresponds to the targeted 0.50 mm of crack extension.
- Samples will be precracked as close as possible to the lengths of the standard E399 tests using compliance crack monitoring techniques.
- Tests follow the E399 test procedure, but are halted at the CMOD corresponding to the K_{Isi} point as determined from previous tests.
- Specimens were marked in order to determine the amount of crack extension.





Interrupted Tests

- Specimens are marked with a 10% sodium hydroxide solution. During marking, specimens are loaded between 50% and 80% of the final test load.
- Crack extension measurements were obtained using a Keyence VR-3200 3D measurement microscope.
- Crack extensions are determined by measuring the cross-sectional area of the middle half of the marked crack extension and dividing by the length of the middle half to determine an average extension value.



Interrupted Tests - Results

- To account for experimental errors with interrupting the tests at the correct point, the measured crack extensions were compared to predicted crack extensions based on a compliance offset line constructed through the maximum load point.
- In all cases, compliance offset overestimates the amount of actual observed crack extension. In the majority of cases, the measured crack extension was less than 50% of the crack extension predicted from compliance offset. Some apparent compliance change corresponding to the K_{Isi} point is expected to be the result of plasticity, so some crack extension less than the target is expected.
- No measured crack extension achieved the target of 0.5 mm, and the ones that were close were actually interrupted past the K_{Isi} point.

Interrupted Tests - Results

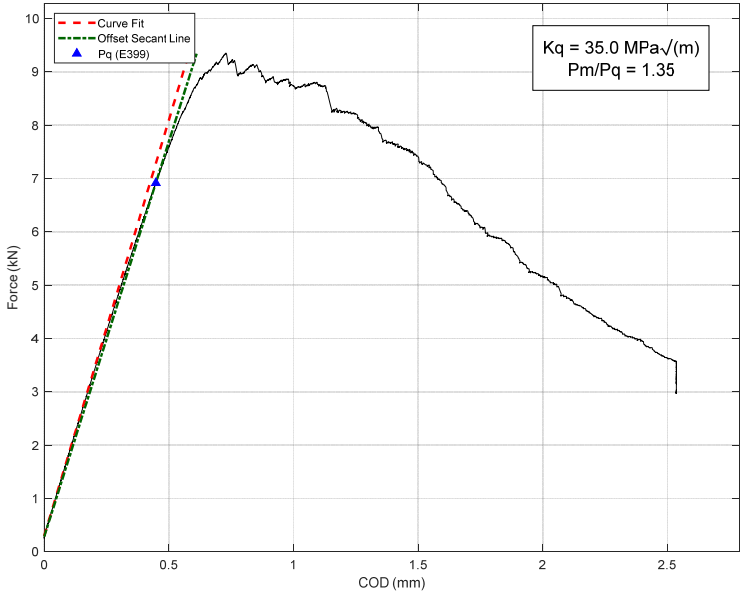
Specimen	W (mm)	B (mm)	$M_{K,limit}$	M_K @ K_{Isi}	K_{Isi} (MPa√m)	$\Delta a_{predicted}$ (mm)	$\Delta a_{measured}$ (mm)	% of $\Delta a_{predicted}$
K-1-2-1	25.4	12.7	0.98	0.96	45.2	0.66	0.29	44
K-1-2-4	25.4	12.7	0.99	1.01	44.1	0.72	0.14	19
K-1-2-10	25.5	12.7	0.98	1.08	42.5	0.62	0.30	48
K-1-4-4	25.4	6.4	0.98	1.27	39.3	0.63	0.21	33
K-1-4-5	25.4	6.4	0.98	1.30	38.9	0.66	0.26	39
K-1-4-6	25.4	6.4	0.99	1.34	38.5	0.67	0.25	37
K-1.5-2-2	38.1	19	1.42	1.45	44.2	0.71	0.35	49
K-1.5-2-3	38.1	19	1.44	1.51	43.6	0.67	0.17	25
K-1.5-2-8	38.1	19	1.41	1.41	44.8	0.61	0.23	38
K-1.5-4-7	38.1	9.5	1.48	1.70	41.7	0.70	0.13	19
K-1.5-4-8	38.1	9.5	1.48	1.74	41.3	0.65	0.23	36
K-1.5-4-10	38.1	9.5	1.49	1.73	41.6	0.67	0.19	29
K-2-2-1	50.8	25.4	1.96	1.88	45.6	0.73	0.45	62
K-2-2-2	50.8	25.4	1.96	1.90	45.4	0.76	0.28	37
K-2-2-8	50.9	25.4	1.98	1.90	45.6	0.77	0.47	61
K-2-4-6	50.8	12.6	1.98	2.18	42.6	0.90	0.45	50
K-2-4-8	50.8	12.6	1.99	2.12	43.2	0.73	0.22	30
K-2-4-9	50.8	12.6	2.00	2.04	44.2	0.68	0.07	10
K-3-2-2	76.2	38.1	3.00	2.84	46.0	0.67	0.22	33
K-3-2-6	76.2	38.1	3.00	2.73	46.9	0.68	0.33	48
K-3-2-7	76.2	38.1	2.99	2.72	46.9	0.70	0.38	55
K-3-4-5	76.2	19.0	2.99	2.95	45.0	0.70	0.27	38
K-3-4-6	76.2	19.0	2.98	3.02	44.4	0.68	0.15	22
K-3-4-8	76.2	19.0	2.99	3.06	44.2	0.68	0.27	40

Forward Plans

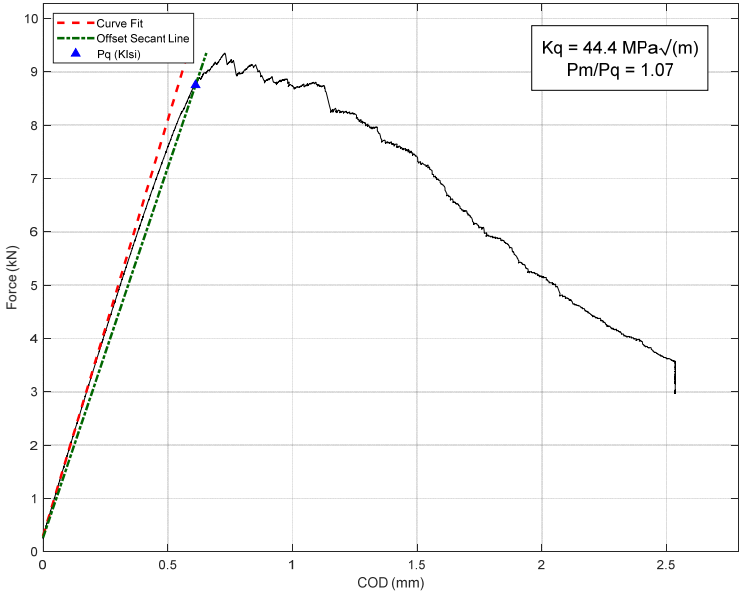
- Run interrupted tests at E399 intercept point.
- Compare K_{Isi} values and crack extensions to J-R curves.
- Compare experimental results to the analytical model published by James.
- Suggestions?

Detailed Results

K-1-2-2 - E399 Test



K_{Ic} Method

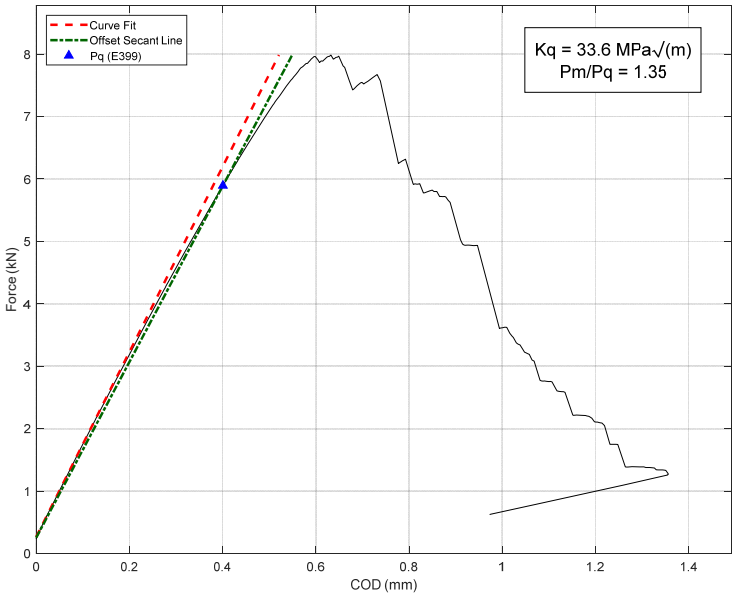


K_{Isi} Method

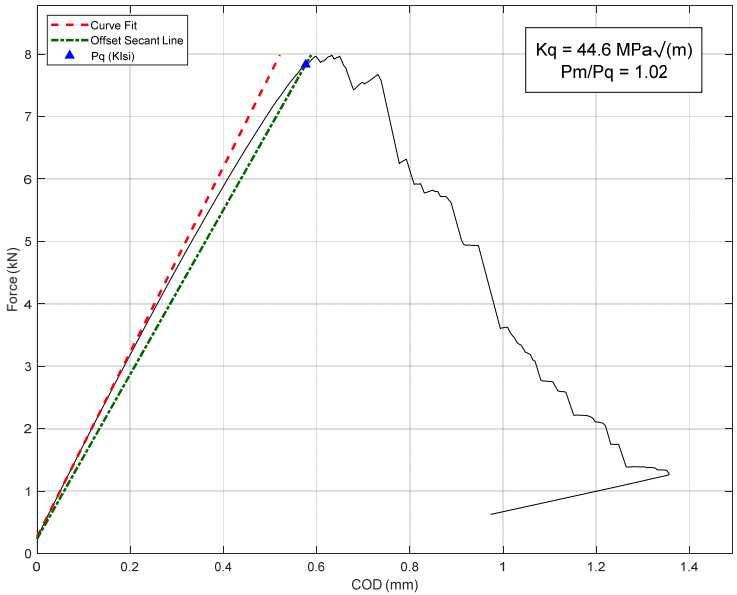
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.2 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	6.916	35.0	1.35	1.60	P_{max}/P_q, Ligament
K_{Isi}	8.753	44.4	1.07	1.00	Valid

K-1-2-8 - E399 Test (Side Grooved)



K_{Ic} Method

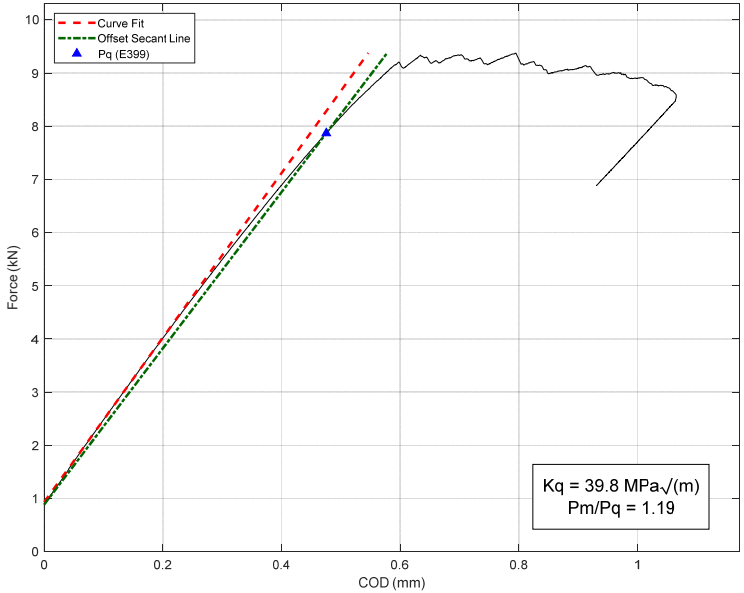


K_{Isi} Method

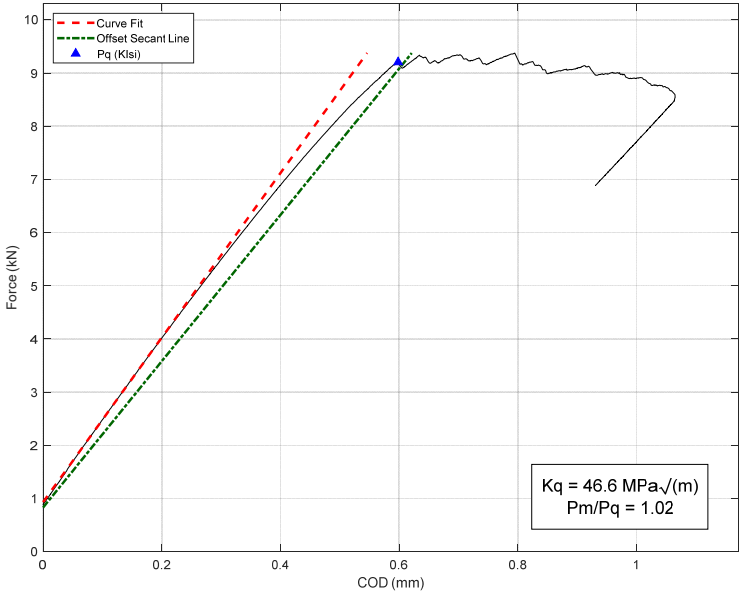
W = 25.4 mm
B = 12.7 mm
B_n = 10.2 mm
a = 13.3 mm
$M_{K,limit}$ (K_{Isi}) = 0.97

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	5.893	33.6	1.35	1.73	P_{max}/P_q, Ligament
K_{Isi}	7.831	44.6	1.02	0.98	Valid

K-1-2-9 - E399 Test



K_{Ic} Method

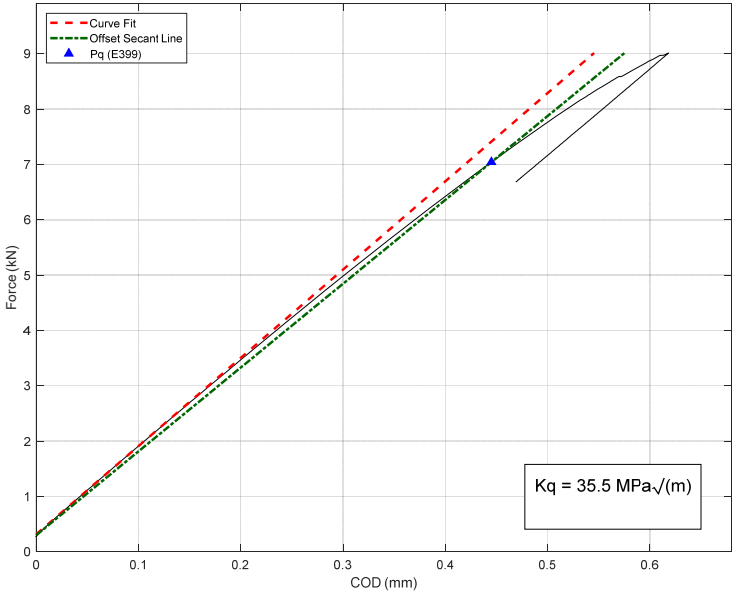


K_{Isi} Method

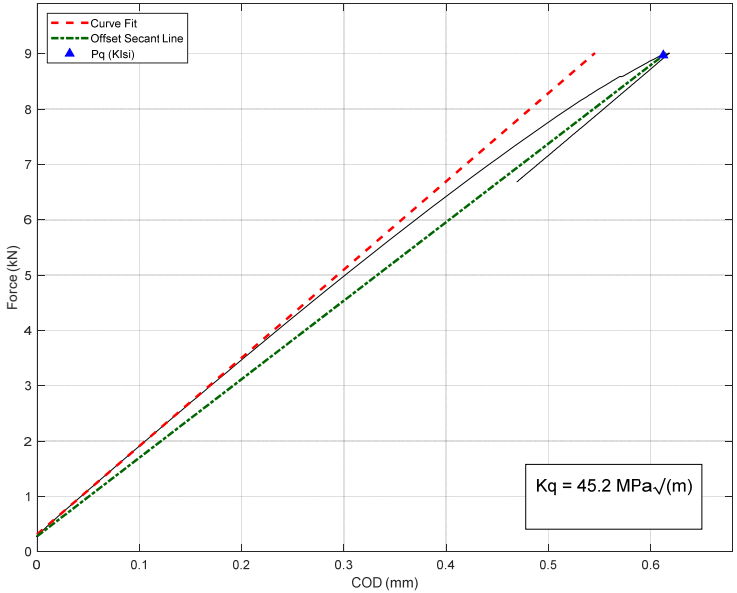
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.2 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	7.867	39.8	1.19	1.23	P_{max}/P_q, Ligament
K_{Isi}	9.204	46.6	1.02	0.90	Ligament

K-1-2-1 - Interrupted Test



K_{Ic} Method

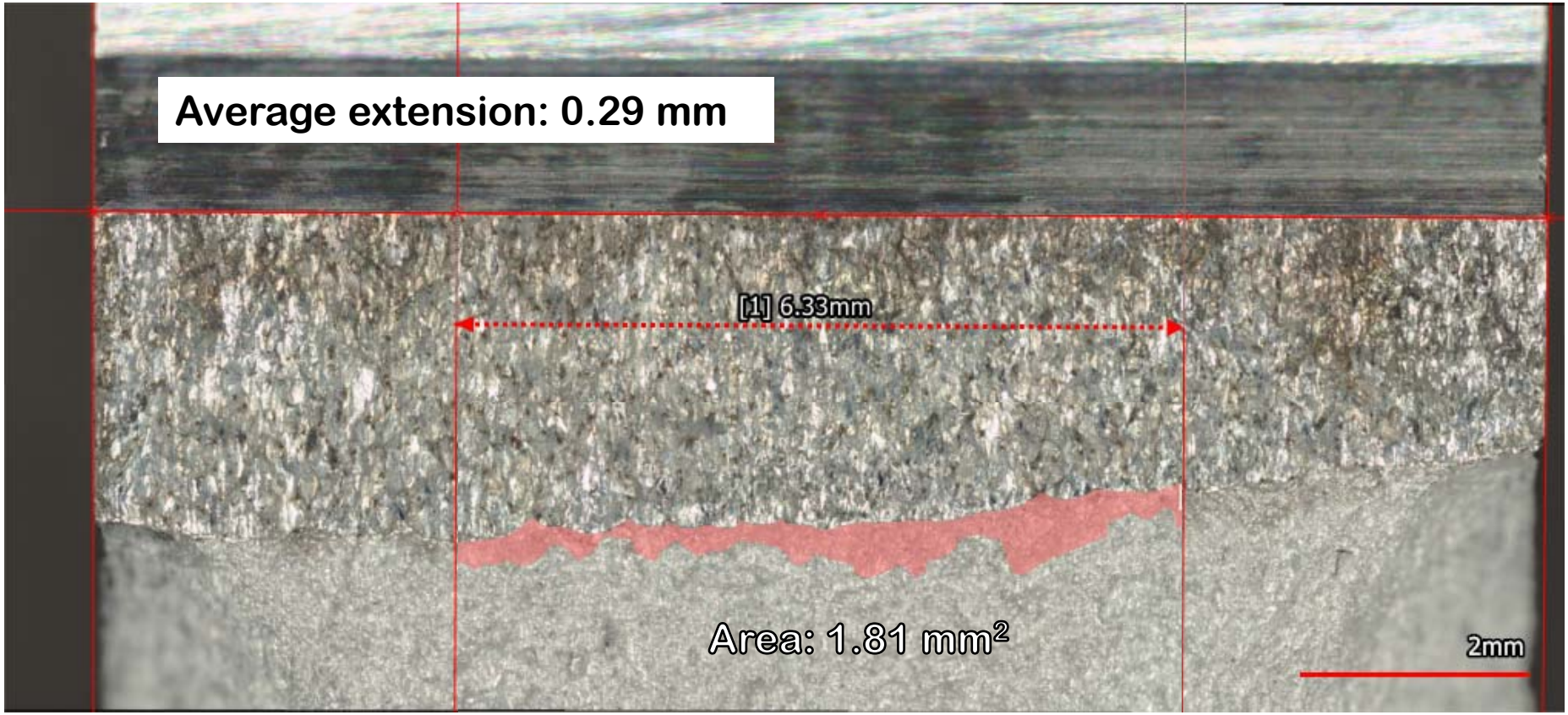


K_{Isi} Method

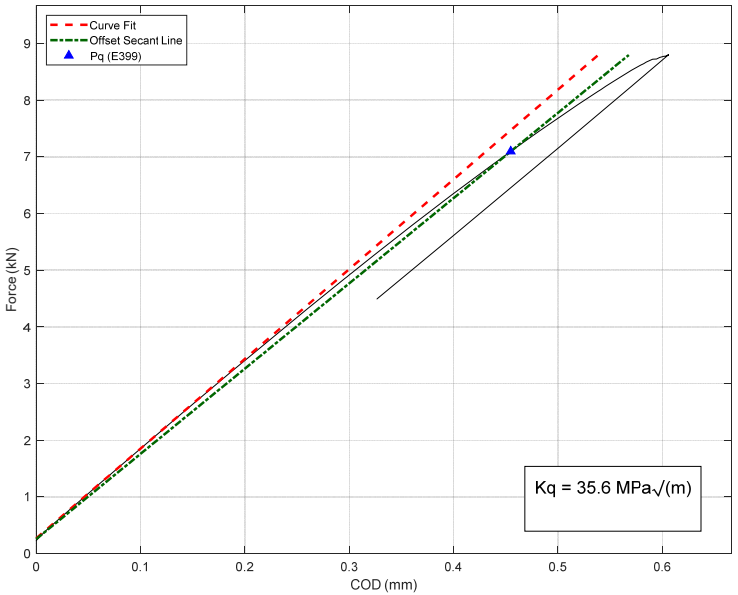
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.1 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	7.041	35.5	---	1.56	Not Valid
K_{Isi}	8.971	45.2	---	0.96	Not Valid

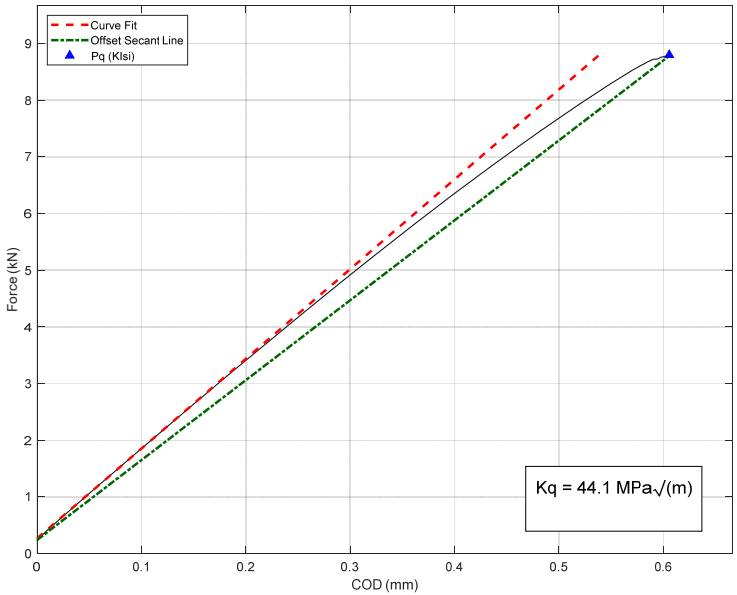
K-1-2-1 – Fracture Surface



K-1-2-4 - Interrupted Test



K_{Ic} Method

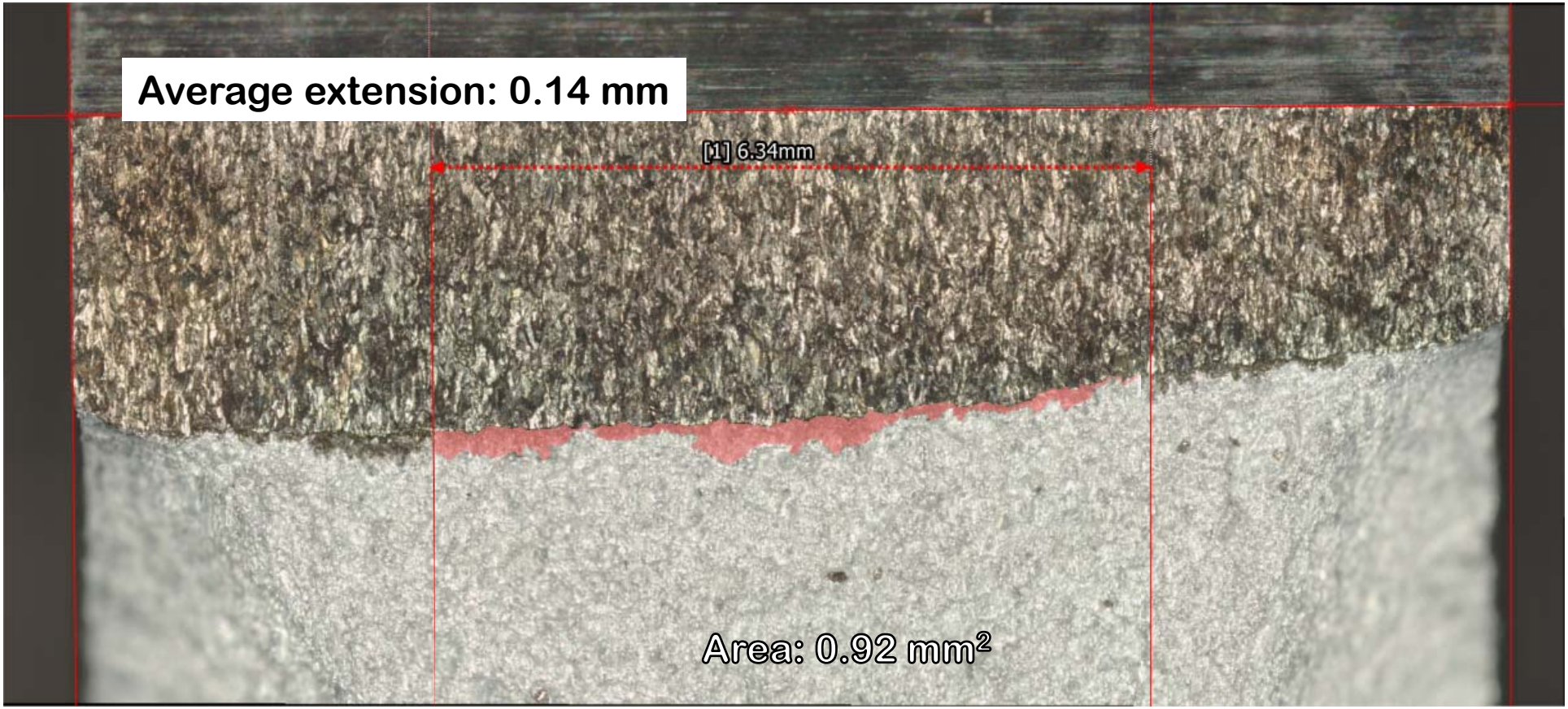


K_{Isi} Method

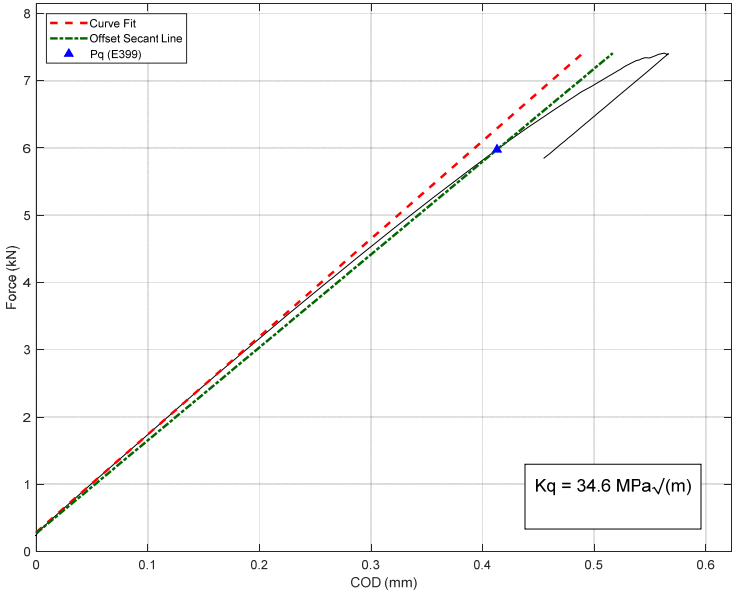
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.1 mm
$M_{K,limit}$ (K_{Isi}) = 0.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	7.095	35.6	---	1.56	Not Valid
K_{Isi}	8.795	44.1	---	1.01	Valid

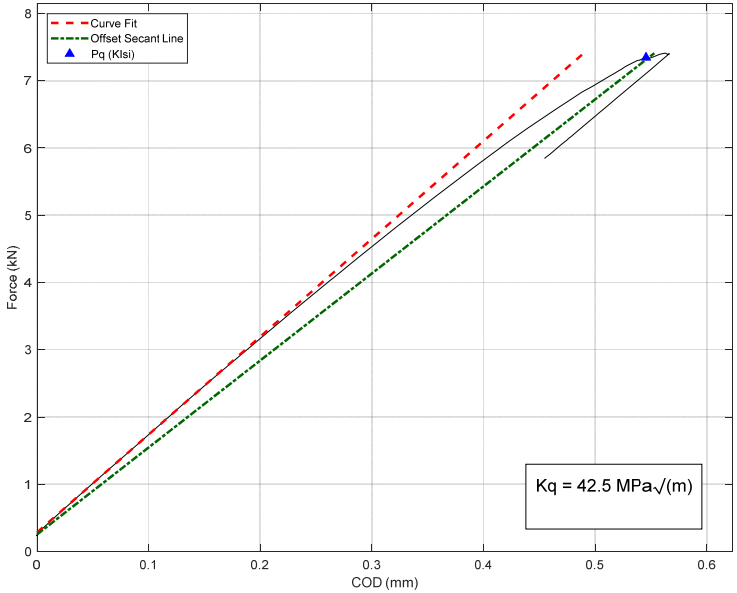
K-1-2-4 – Fracture Surface



K-1-2-10 - Interrupted Test



K_{Ic} Method

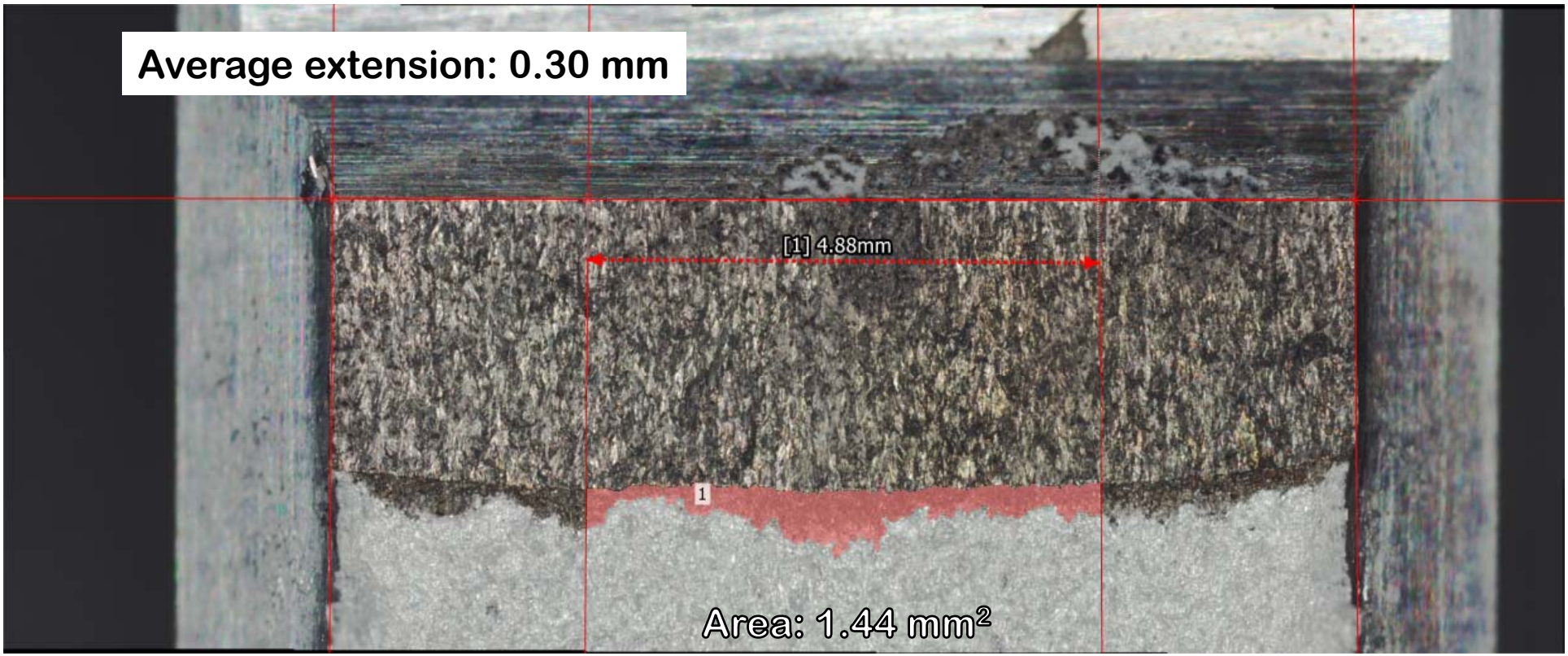


K_{Isi} Method

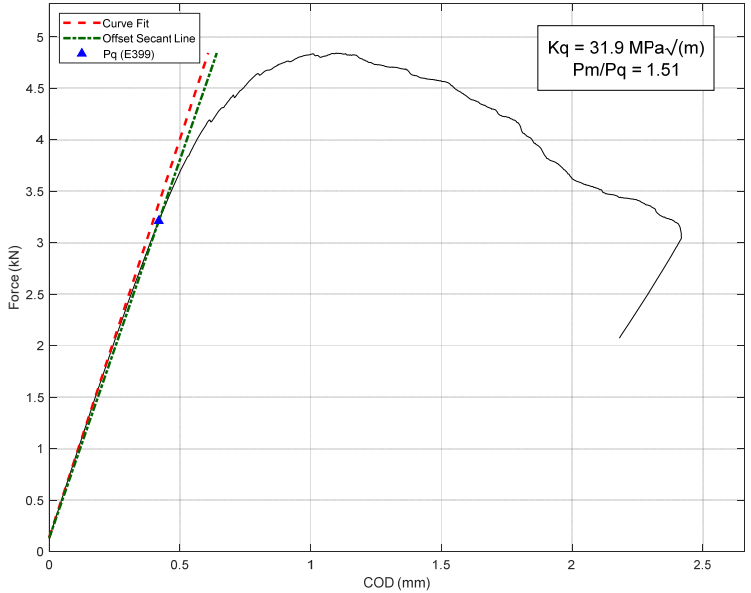
W = 25.5 mm
B = 12.7 mm
B_n = 9.8 mm
a = 13.2 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	5.977	34.6	---	1.63	Not Valid
K_{Isi}	7.344	42.5	---	1.08	Valid

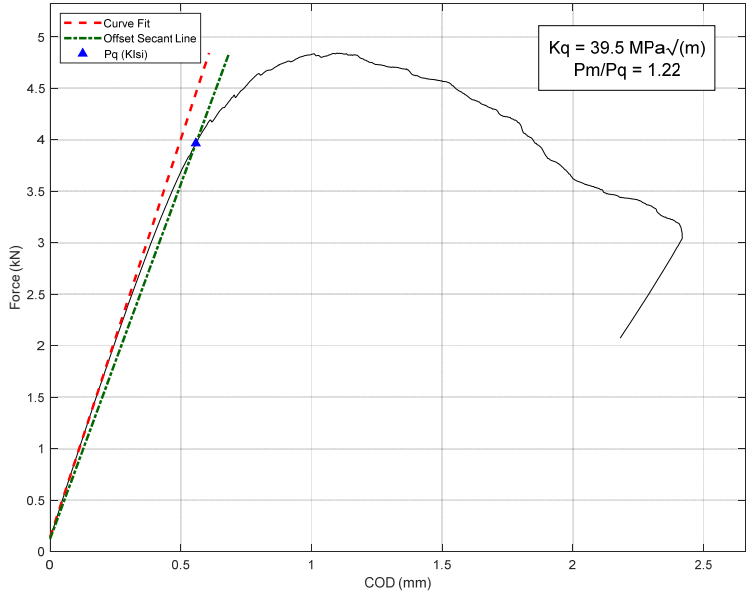
K-1-2-10 – Fracture Surface



K-1-4-1 - E399 Test



K_{Ic} Method

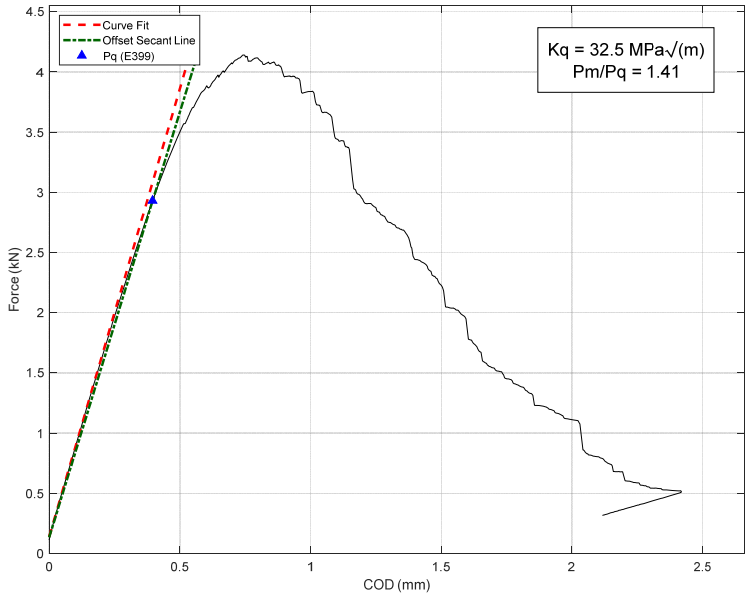


K_{Isi} Method

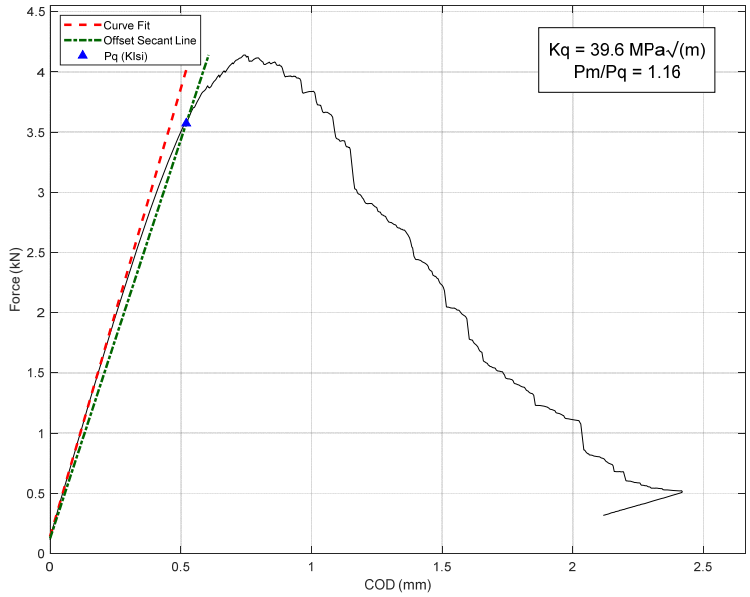
W = 25.4 mm
B = 6.3 mm
B_n = 6.3 mm
a = 13.0 mm
$M_{K,limit}$ (K_{Isi}) = 0.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	3.211	31.9	1.51	1.94	P_{max}/P_q, Ligament
K_{Isi}	3.965	39.5	1.22	1.27	Valid

K-1-4-2 - E399 Test (Side Grooved)



K_{Ic} Method

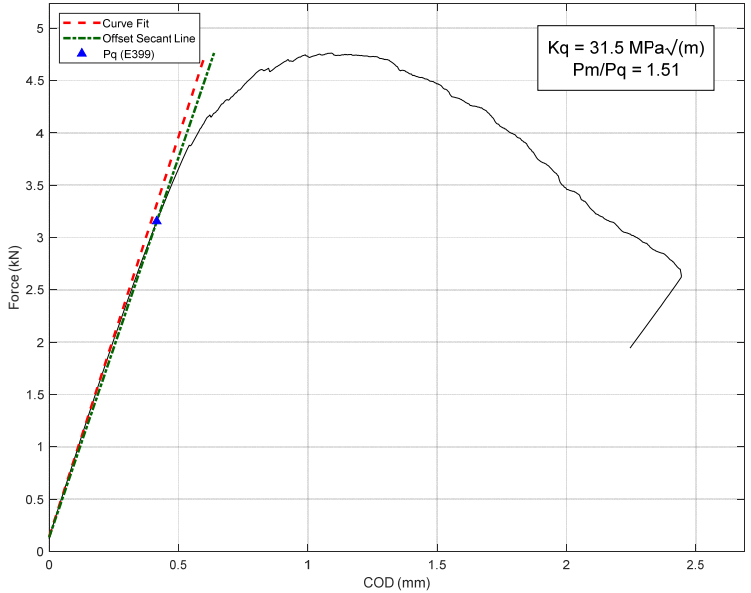


K_{Isi} Method

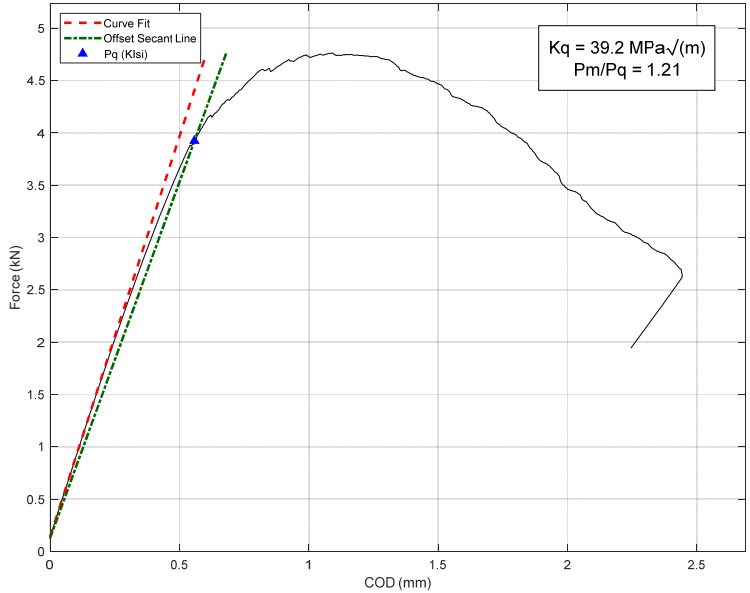
W = 25.4 mm
B = 6.4 mm
B_n = 5.2 mm
a = 13.1 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	2.930	32.5	1.41	1.85	P_{max}/P_q, Ligament
K_{Isi}	3.572	39.6	1.16	1.25	Valid

K-1-4-8 - E399 Test



K_{Ic} Method

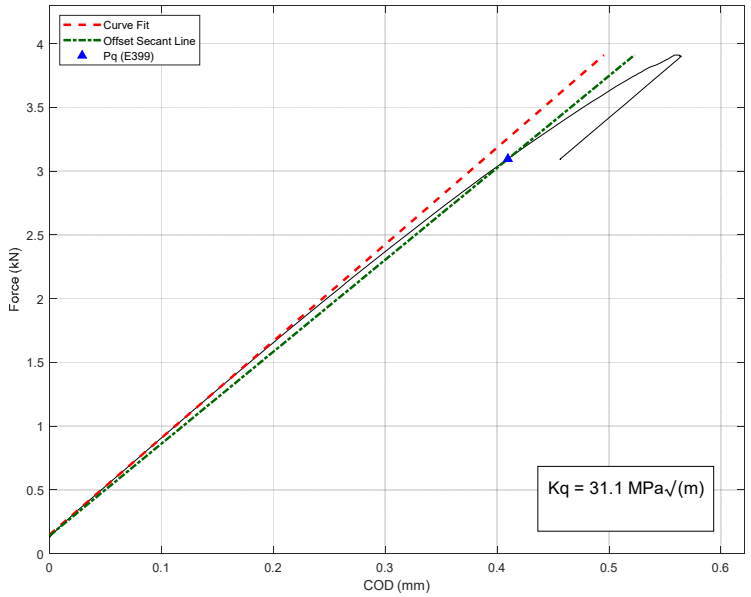


K_{Isi} Method

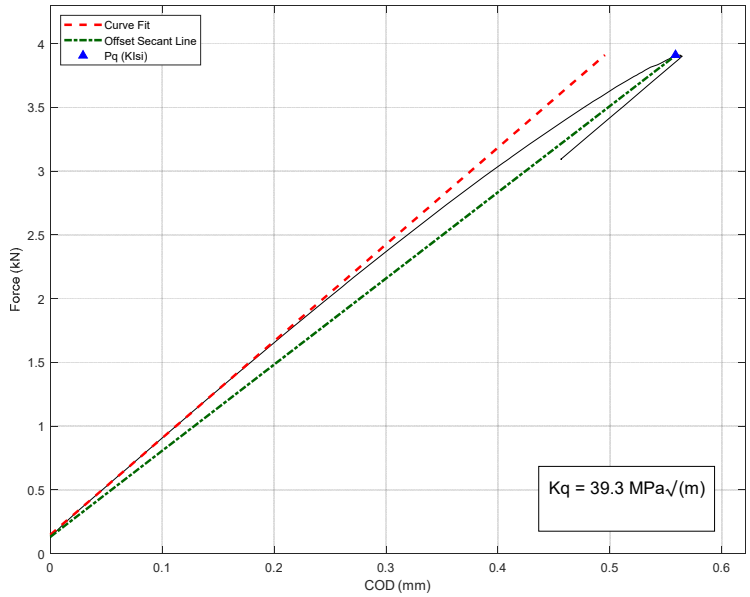
W = 25.4 mm
B = 6.4 mm
B_n = 6.4 mm
a = 13.1 mm
$M_{K,limit}$ (K_{Isi}) = 0.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	3.155	31.5	1.51	1.99	P_{max}/P_q, Ligament
K_{Isi}	3.924	39.2	1.21	1.28	Valid

K-1-4-4 - Interrupted Test



K_{Ic} Method

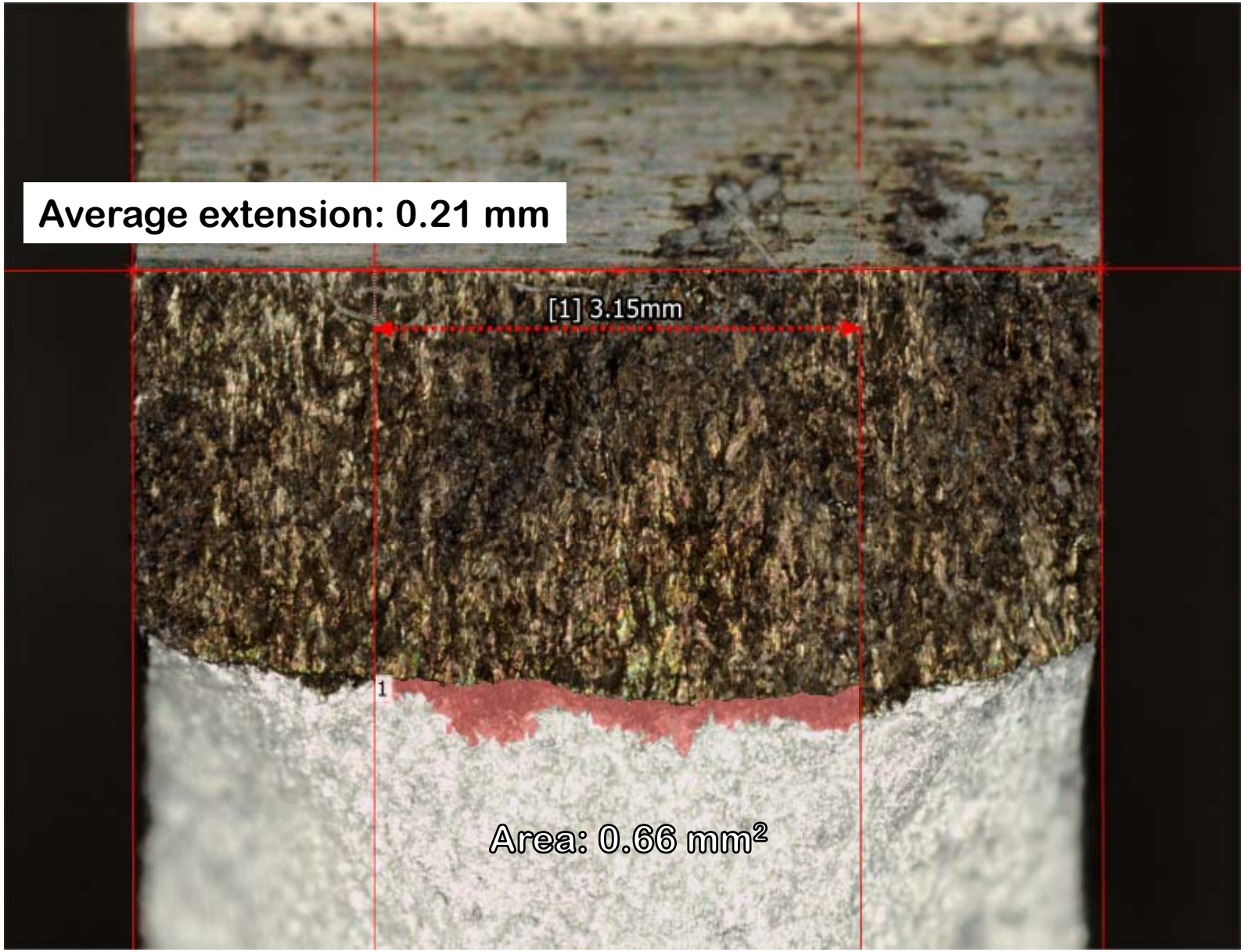


K_{Isi} Method

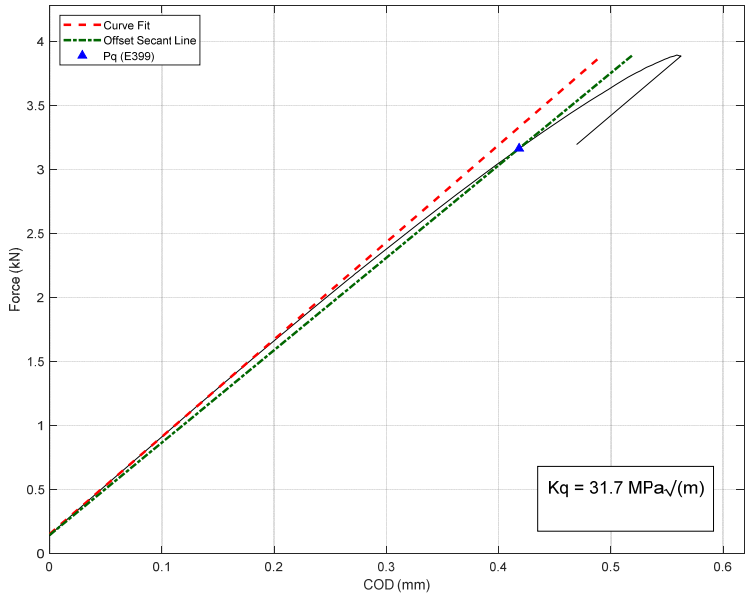
W = 25.4 mm
B = 6.4 mm
B_n = 6.4 mm
a = 13.2 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	3.095	31.1	---	2.02	Not Valid
K_{Isi}	3.911	39.3	---	1.27	Valid

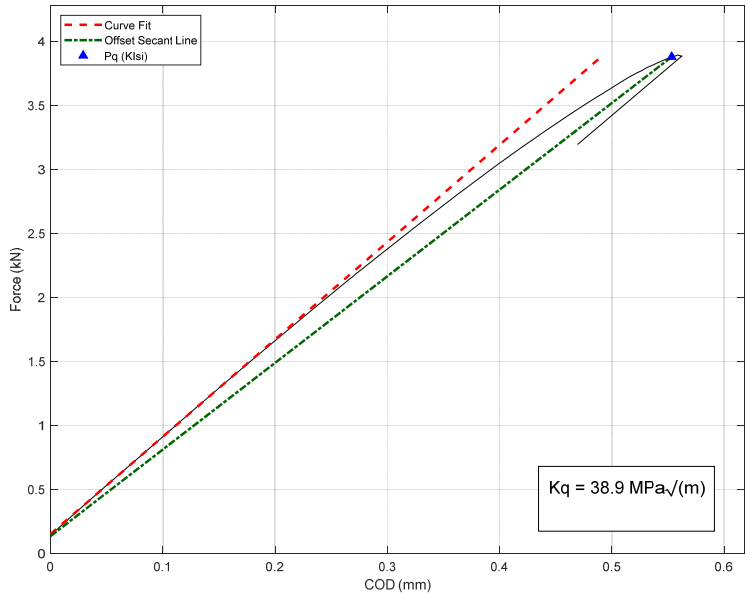
K-1-4-4 – Fracture Surface



K-1-4-5 - Interrupted Test



K_{Ic} Method

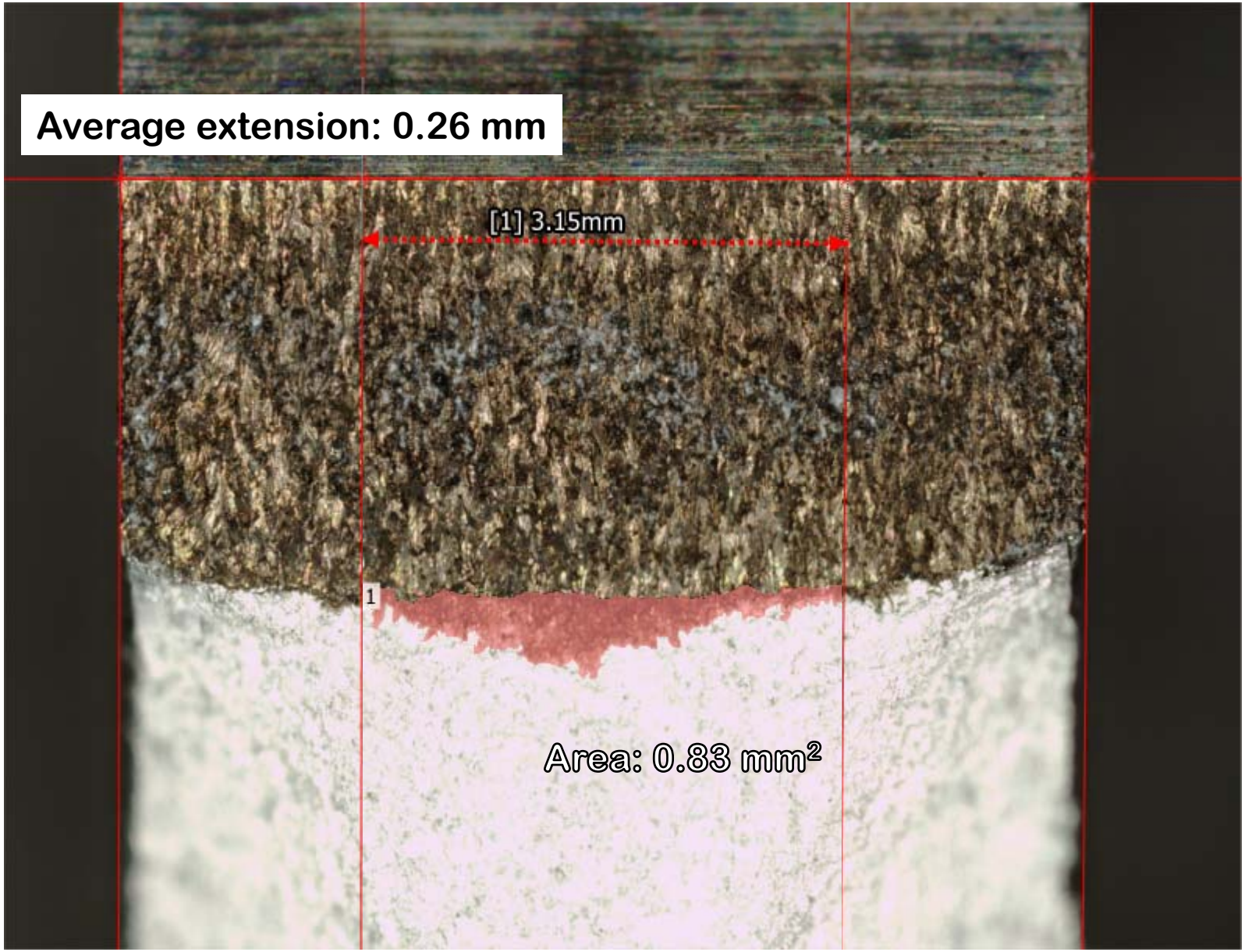


K_{Isi} Method

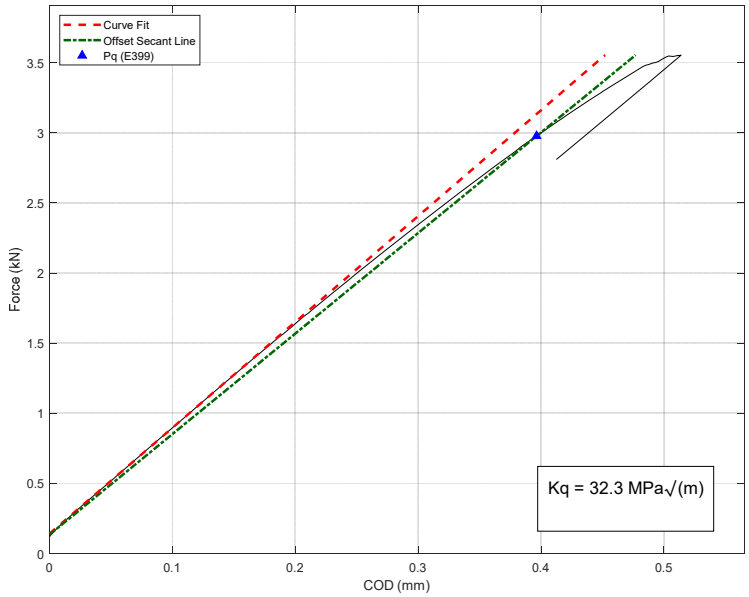
W = 25.4 mm
B = 6.4 mm
B_n = 6.4 mm
a = 13.1 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	3.166	31.7	---	1.95	Not Valid
K_{Isi}	3.881	38.9	---	1.30	Valid

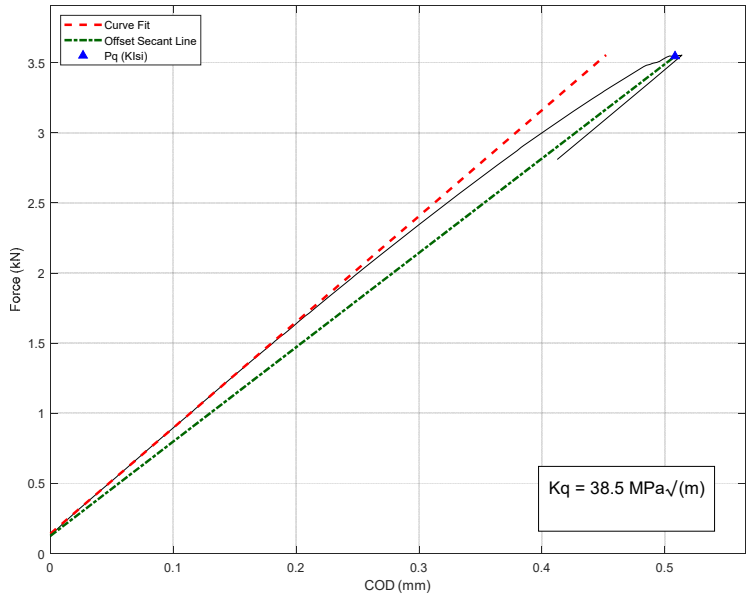
K-1-4-5 – Fracture Surface



K-1-4-6 - Interrupted Test



K_{Ic} Method

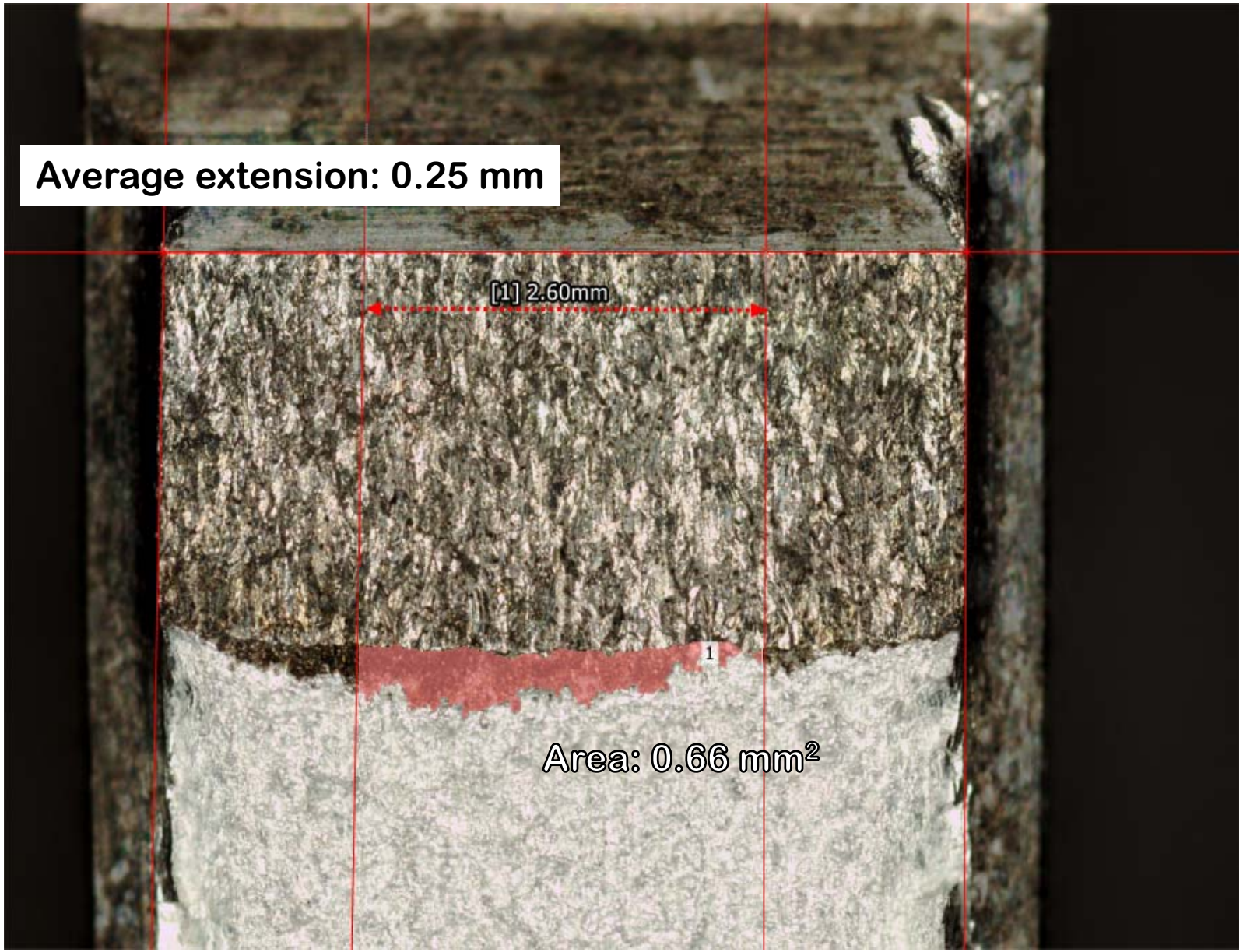


K_{Isi} Method

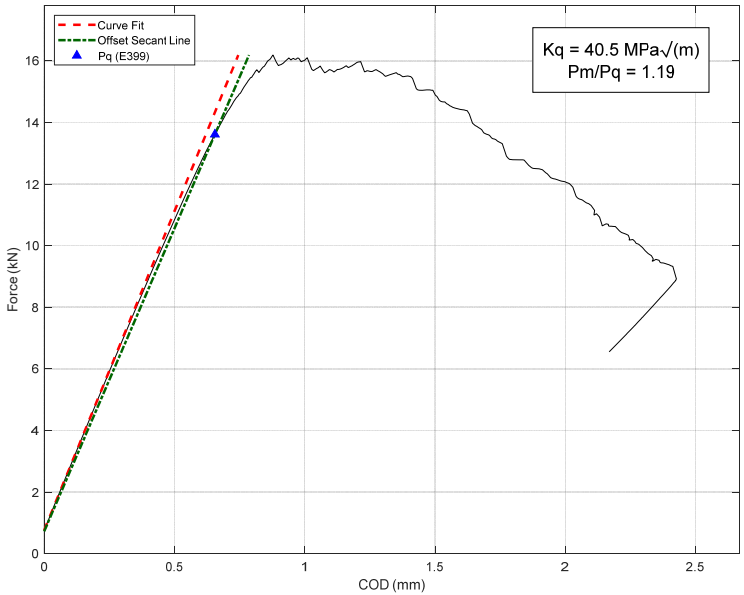
W = 25.4 mm
B = 6.4 mm
B_n = 5.3 mm
a = 13.0 mm
$M_{K,limit}$ (K_{Isi}) = 0.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	2.976	32.3	---	1.90	Not Valid
K_{Isi}	3.545	38.5	---	1.34	Valid

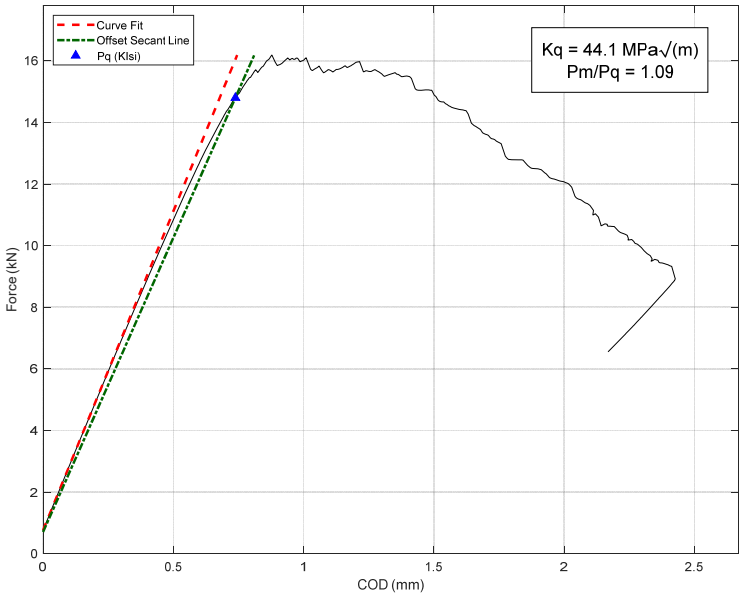
K-1-4-6 – Fracture Surface



K-15-2-5 - E399 Test



K_{Ic} Method

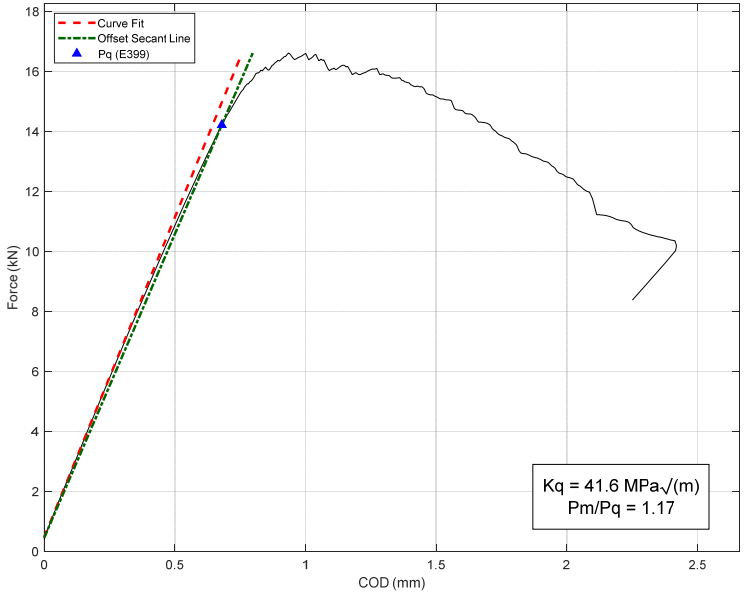


K_{Isi} Method

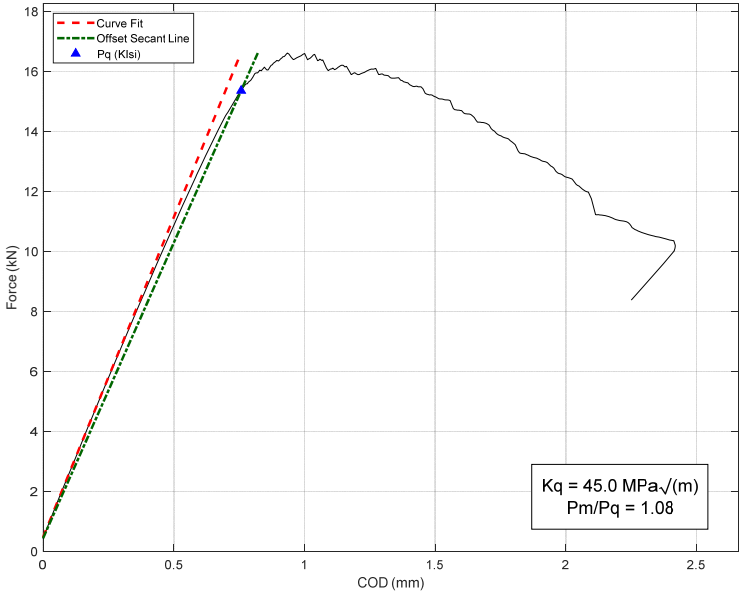
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.6 mm
$M_{K,limit}$ (K_{Isi}) = 1.39

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	13.608	40.5	1.19	1.70	P_{max}/P_q, Ligament
K_{Isi}	14.799	44.1	1.09	1.43	Valid

K-15-2-6 - E399 Test



K_{Ic} Method

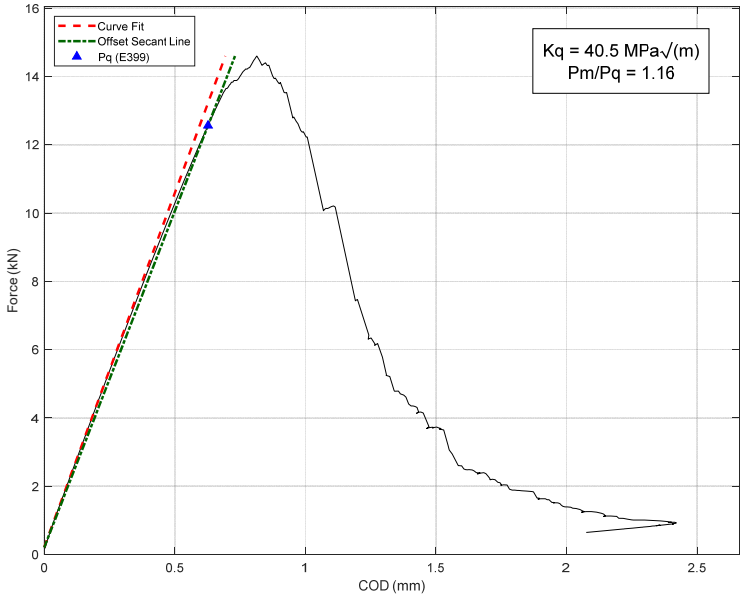


K_{Isi} Method

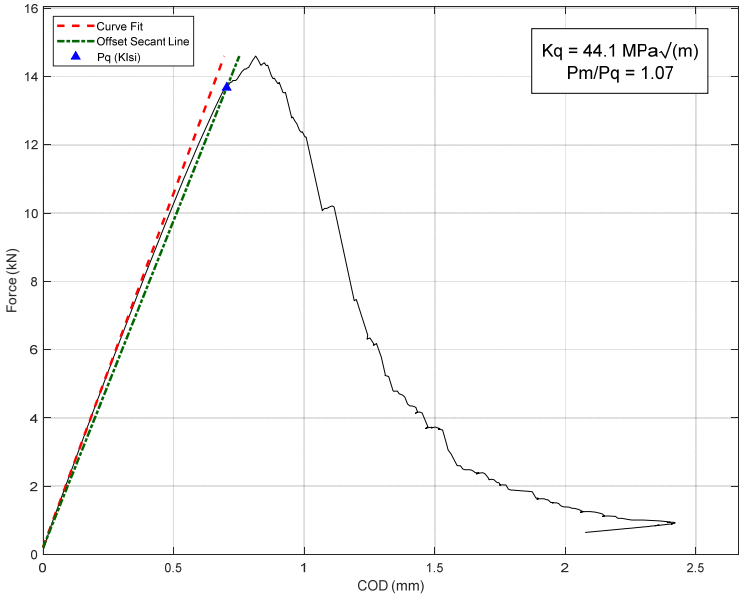
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.4 mm
$M_{K,limit}$ (K_{Isi}) = 1.41

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	14.220	41.6	1.17	1.63	P_{max}/P_q, Ligament
K_{Isi}	15.363	45.0	1.08	1.40	Ligament

K-15-2-10 - E399 Test (Side Grooved)



K_{Ic} Method

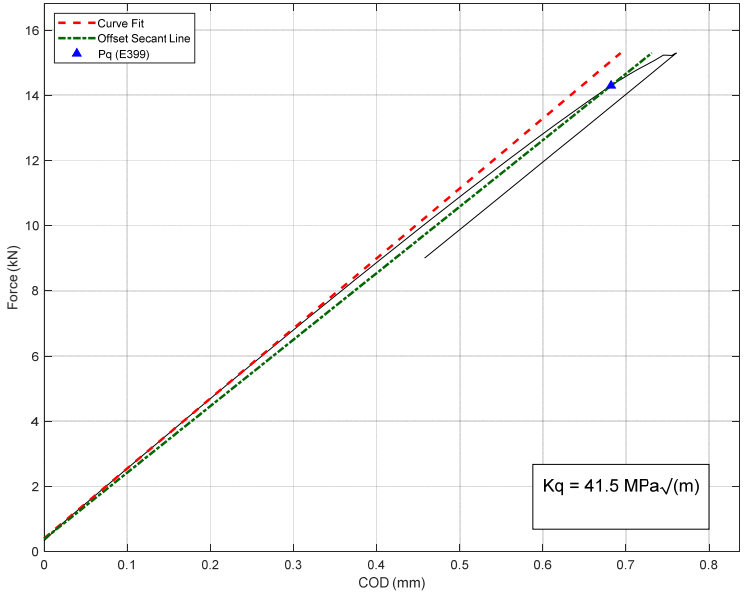


K_{Isi} Method

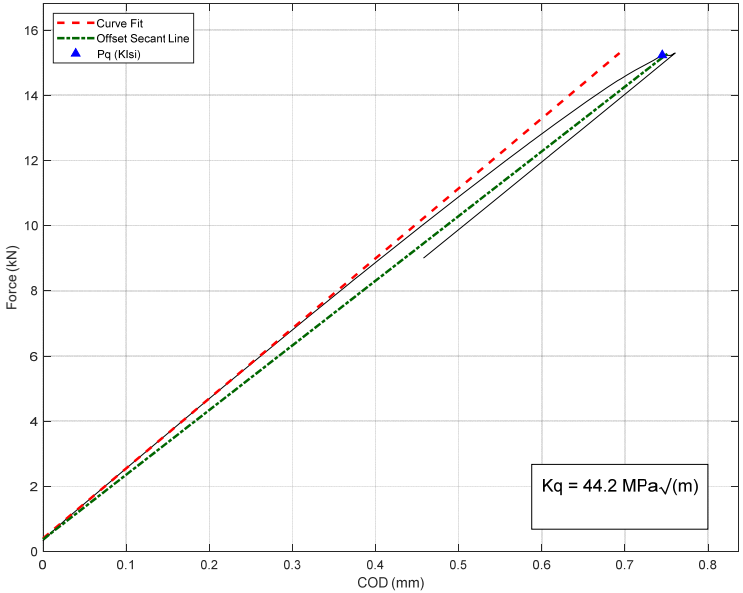
W = 38.1 mm
B = 19.0 mm
B_n = 15.3 mm
a = 20.3 mm
$M_{K,limit}$ (K_{Isi}) = 1.42

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	12.562	40.5	1.16	1.74	P_{max}/P_q, Ligament
K_{Isi}	13.673	44.1	1.07	1.47	Valid

K-15-2-2 - Interrupted Test



K_{Ic} Method

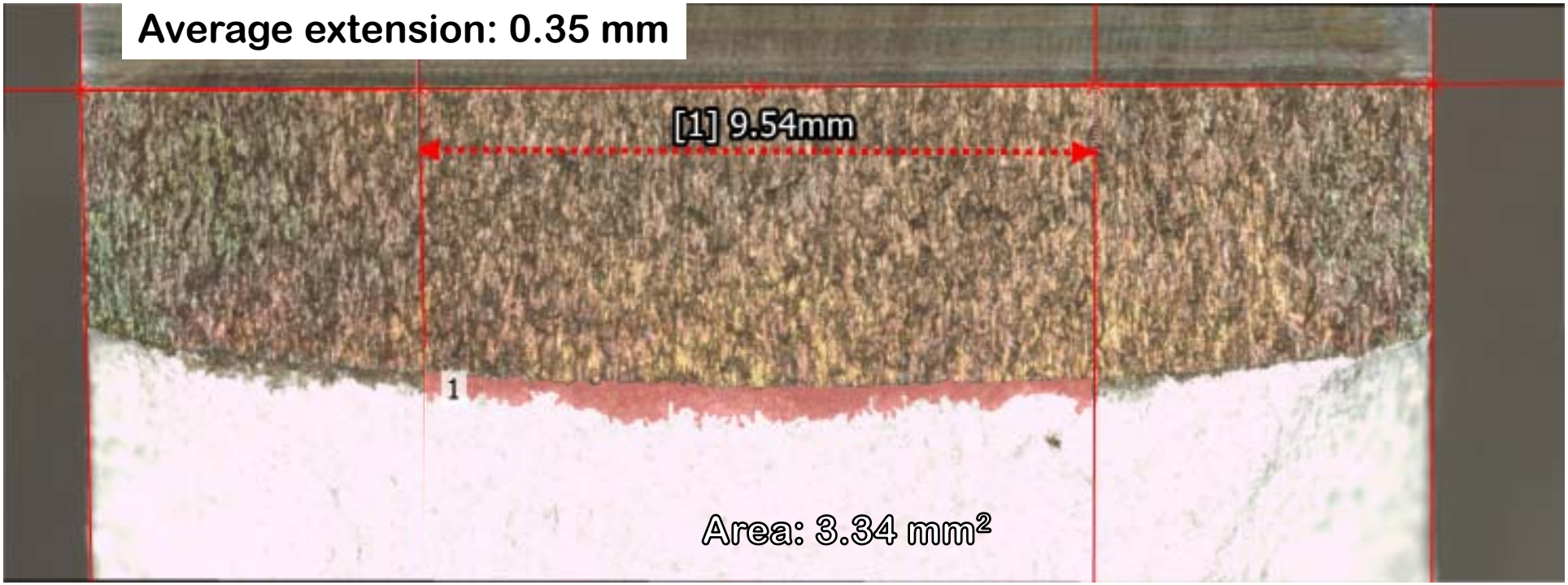


K_{Isi} Method

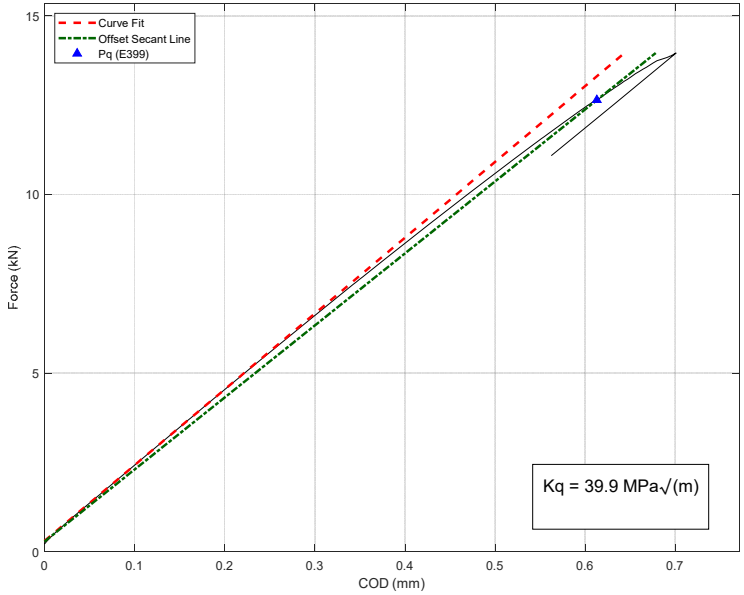
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.4 mm
$M_{K,limit}$ (K_{Isi}) = 1.42

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	14.295	41.5	---	1.65	Not Valid
K_{Isi}	15.230	44.2	---	1.45	Valid

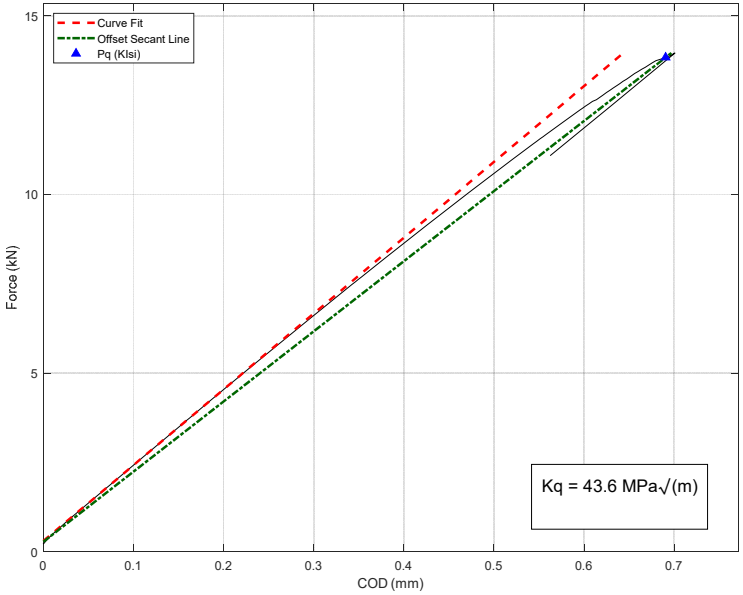
K-1.5-2-2 – Fracture Surface



K-15-2-3 - Interrupted Test



K_{Ic} Method

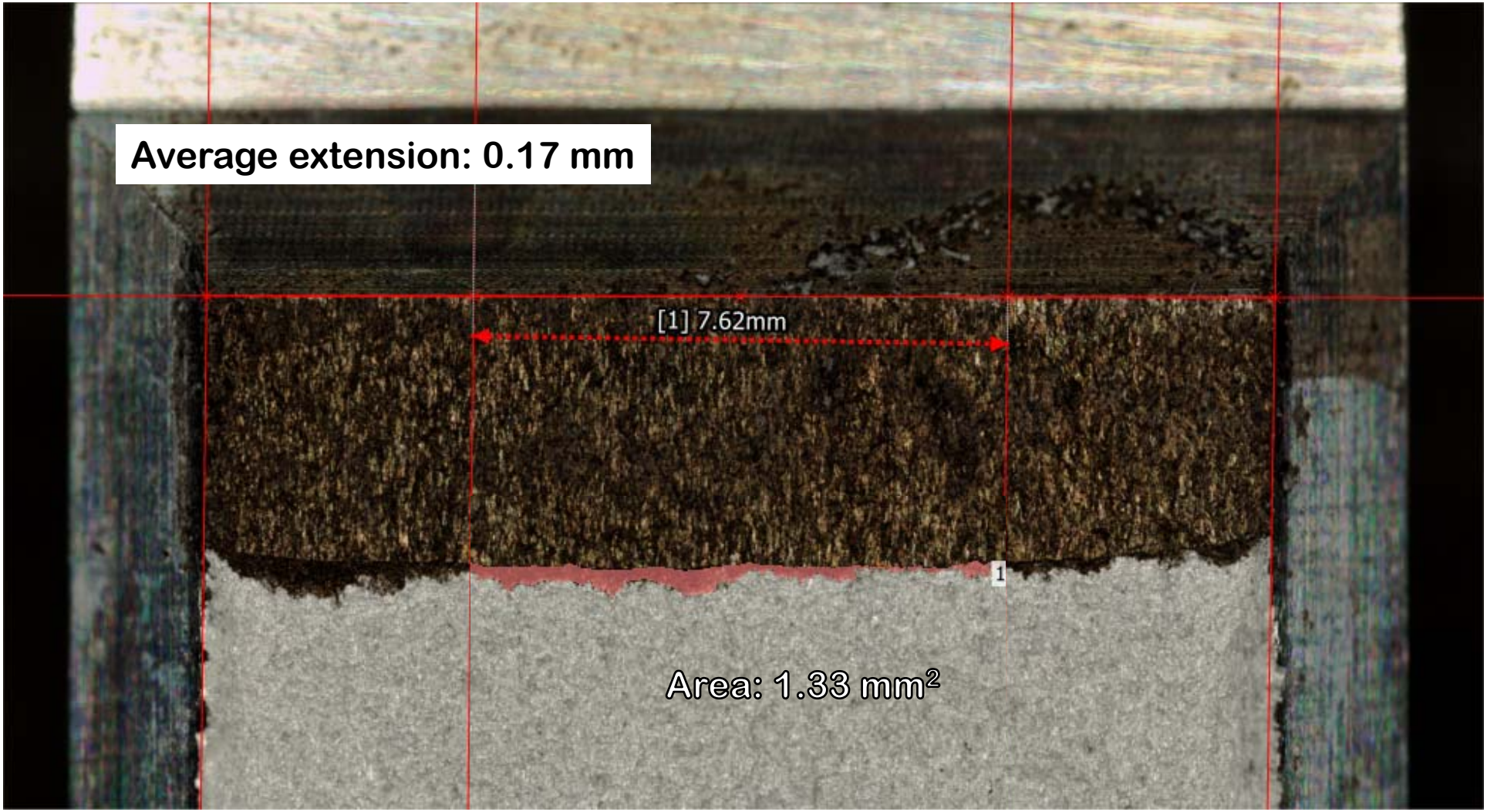


K_{Isi} Method

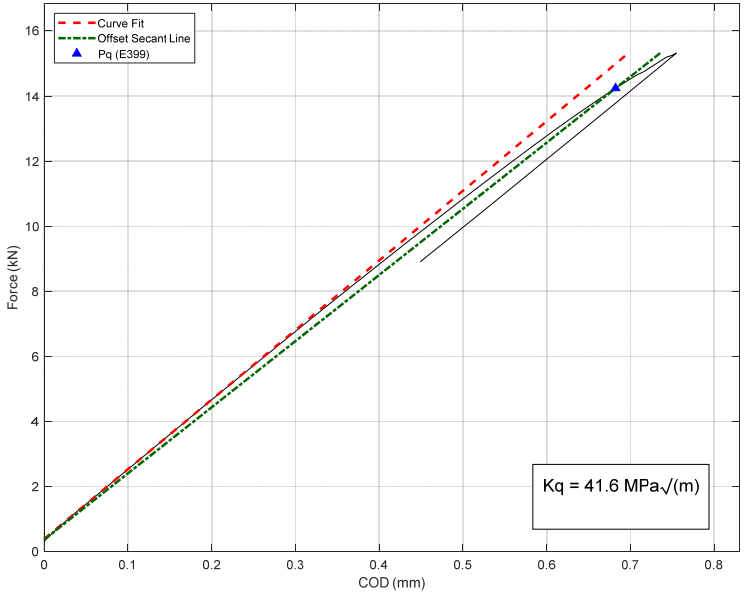
W = 38.1 mm
B = 19.0 mm
B_n = 15.3 mm
a = 20.0 mm
$M_{K,limit}$ (K_{Isi}) = 1.44

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	12.643	39.9	---	1.81	Not Valid
K_{Isi}	13.834	43.6	---	1.51	Valid

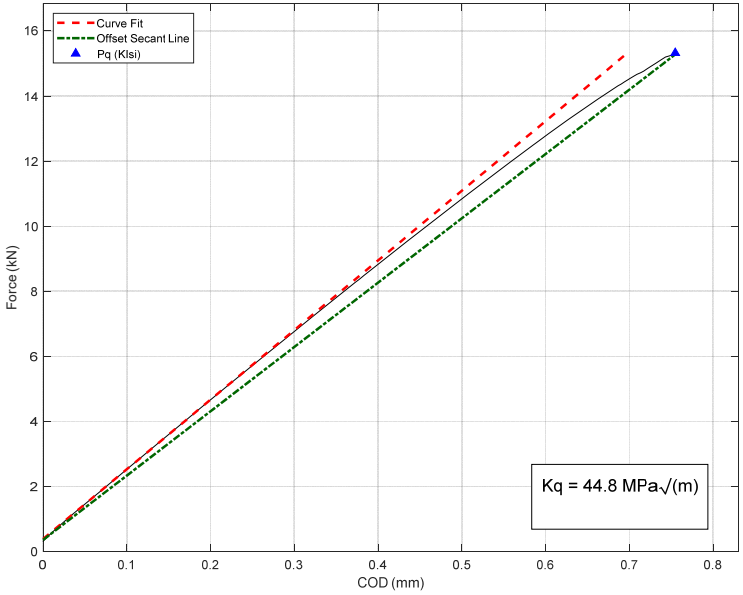
K-1.5-2-3 – Fracture Surface



K-15-2-8 - Interrupted Test



K_{Ic} Method

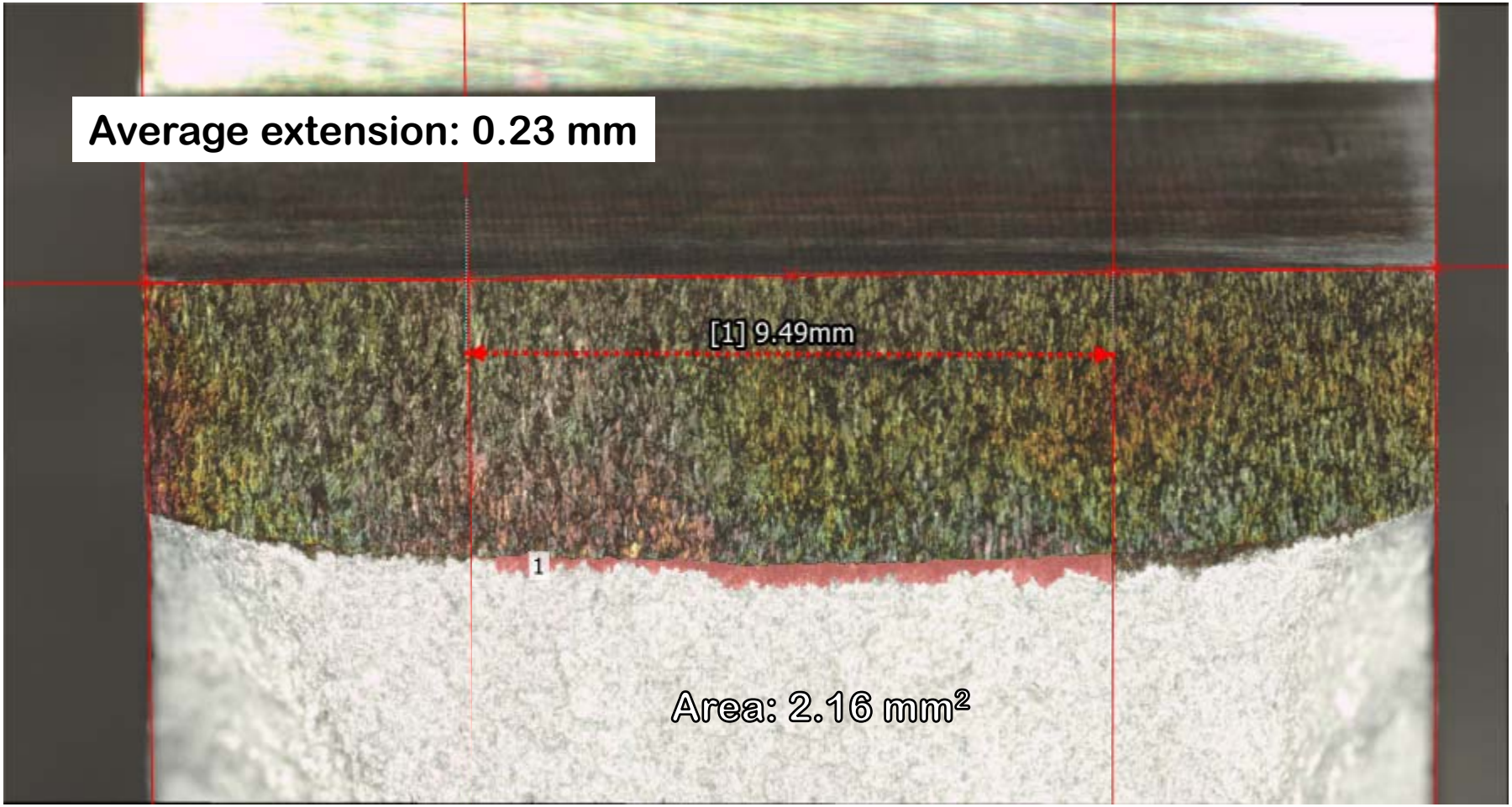


K_{Isi} Method

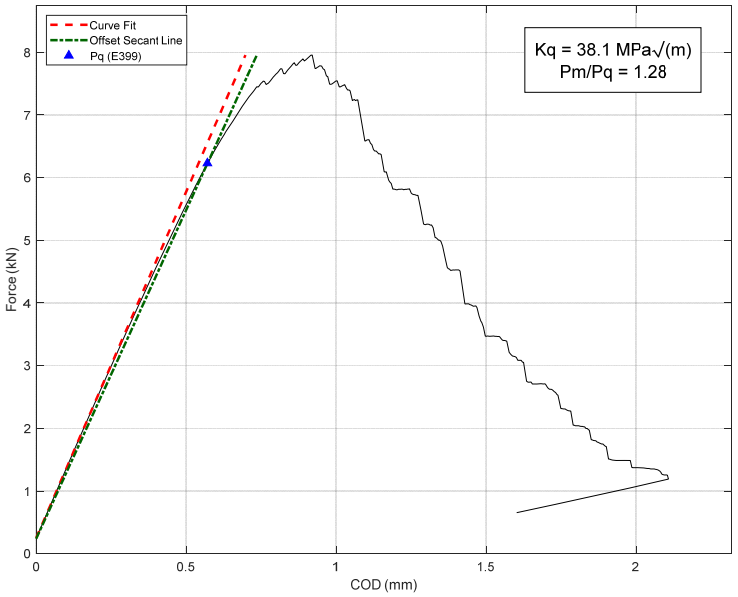
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.4 mm
$M_{K,limit}$ (K_{Isi}) = 1.41

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	14.242	41.6	---	1.63	Not Valid
K_{Isi}	15.324	44.8	---	1.41	Not Valid

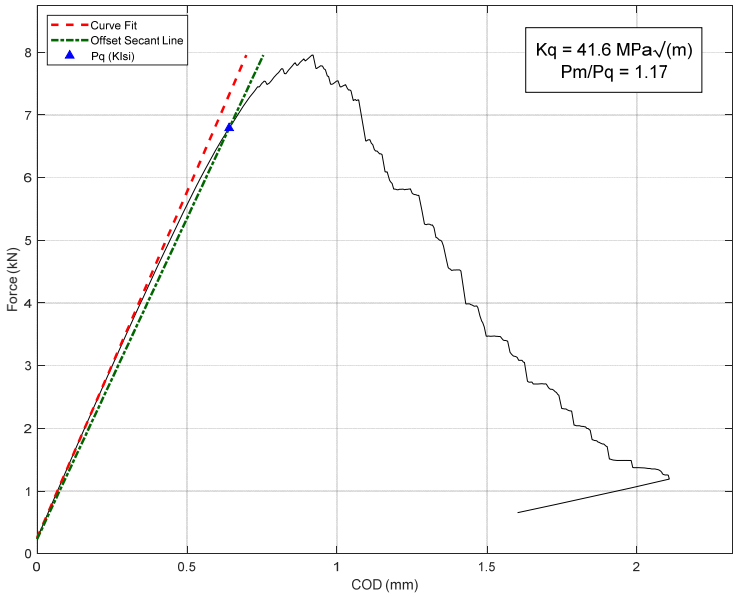
K-1.5-2-8 – Fracture Surface



K-15-4-2 - E399 Test (Side Grooved)



K_{Ic} Method

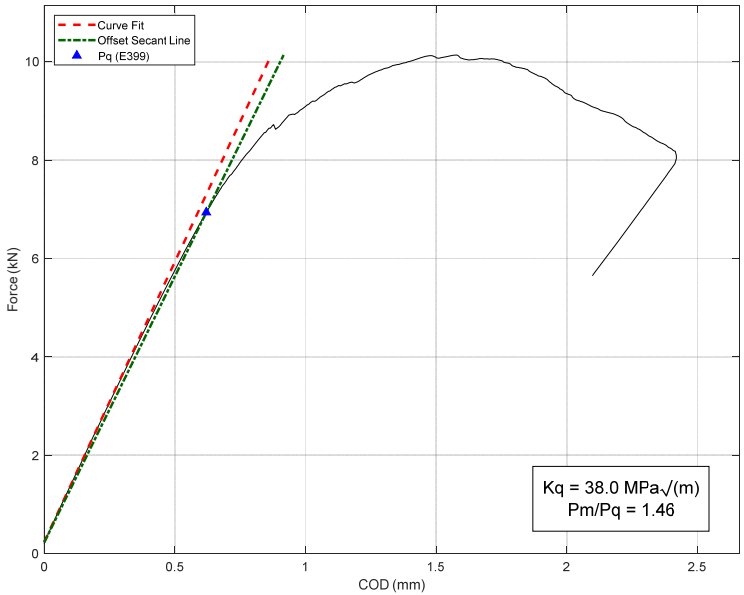


K_{Isi} Method

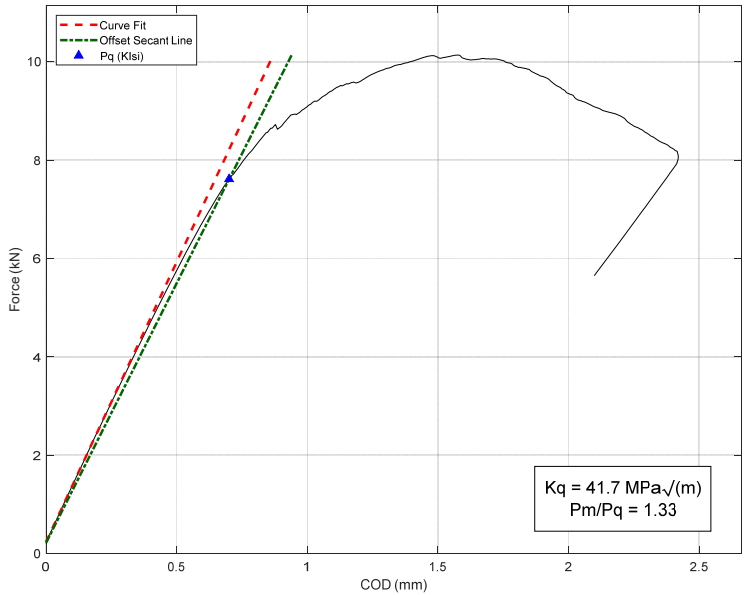
W = 38.1 mm
B = 9.5 mm
B_n = 7.5 mm
a = 19.6 mm
$M_{K,limit}$ (K_{Isi}) = 1.48

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	6.228	38.1	1.28	2.04	P_{max}/P_q, Ligament
K_{Isi}	6.789	41.6	1.17	1.72	Valid

K-15-4-3 - E399 Test



K_{Ic} Method

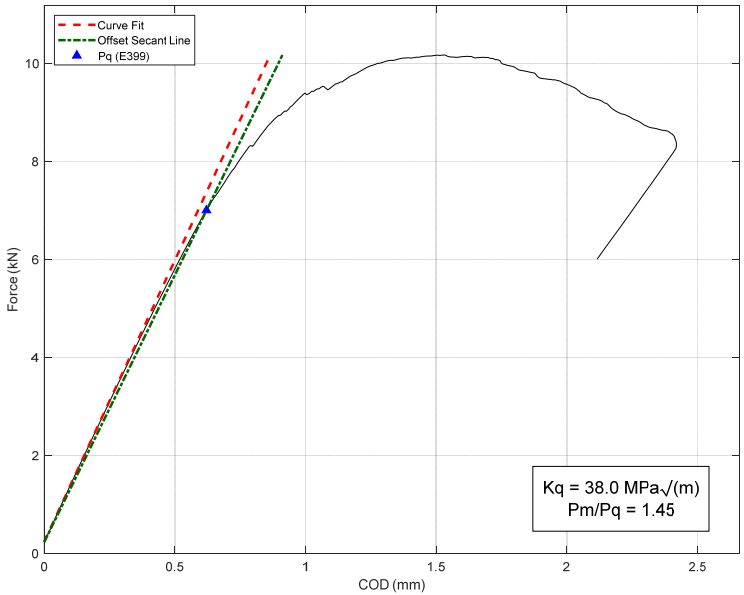


K_{Isi} Method

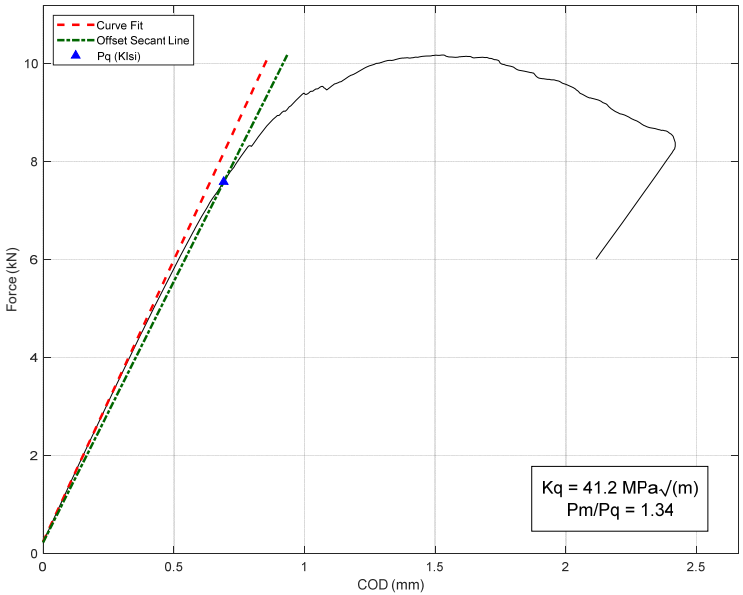
W = 38.1 mm
B = 9.5 mm
B_n = 9.5 mm
a = 19.6 mm
$M_{K,limit}$ (K_{Isi}) = 1.47

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	6.938	38.0	1.46	2.04	P_{max}/P_q, Ligament
K_{Isi}	7.612	41.7	1.33	1.69	Valid

K-15-4-6 - E399 Test



K_{Ic} Method

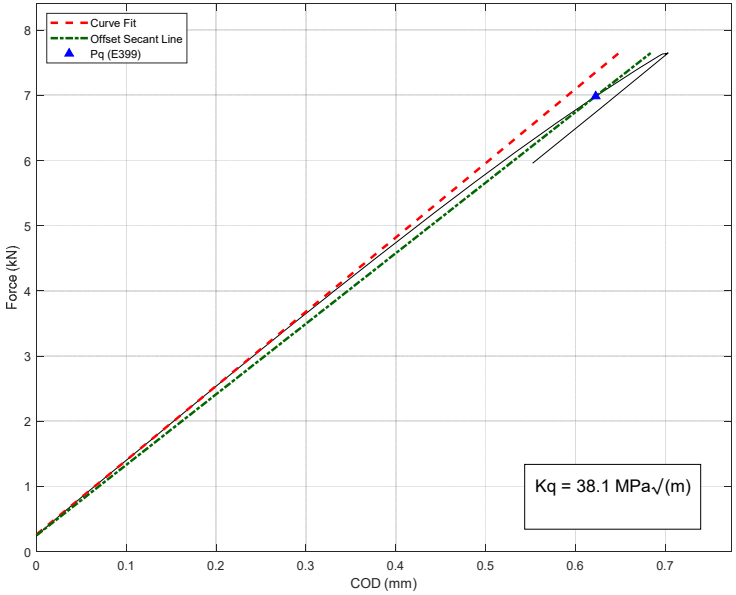


K_{Isi} Method

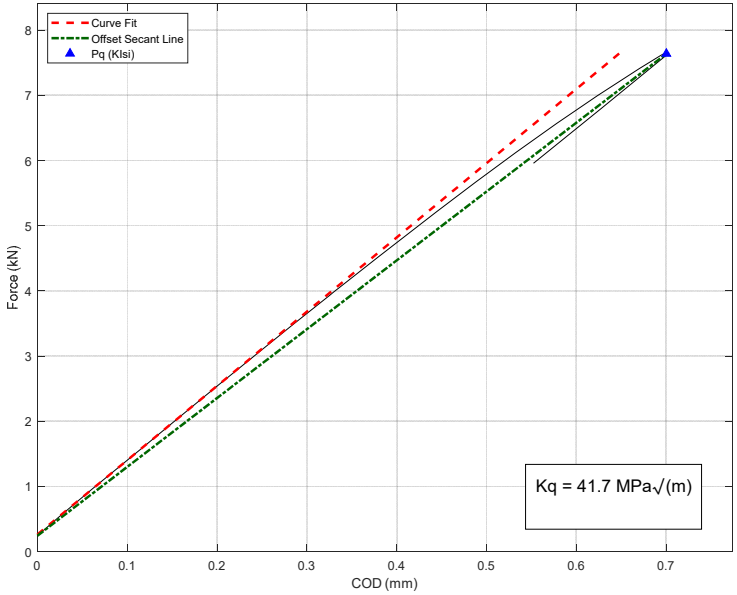
W = 38.1 mm
B = 9.5 mm
B_n = 9.5 mm
a = 19.5 mm
$M_{K,limit}$ (K_{Isi}) = 1.49

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	7.002	38.0	1.45	2.06	P_{max}/P_q, Ligament
K_{Isi}	7.585	41.2	1.34	1.75	Valid

K-15-4-7 - Interrupted Test



K_{Ic} Method

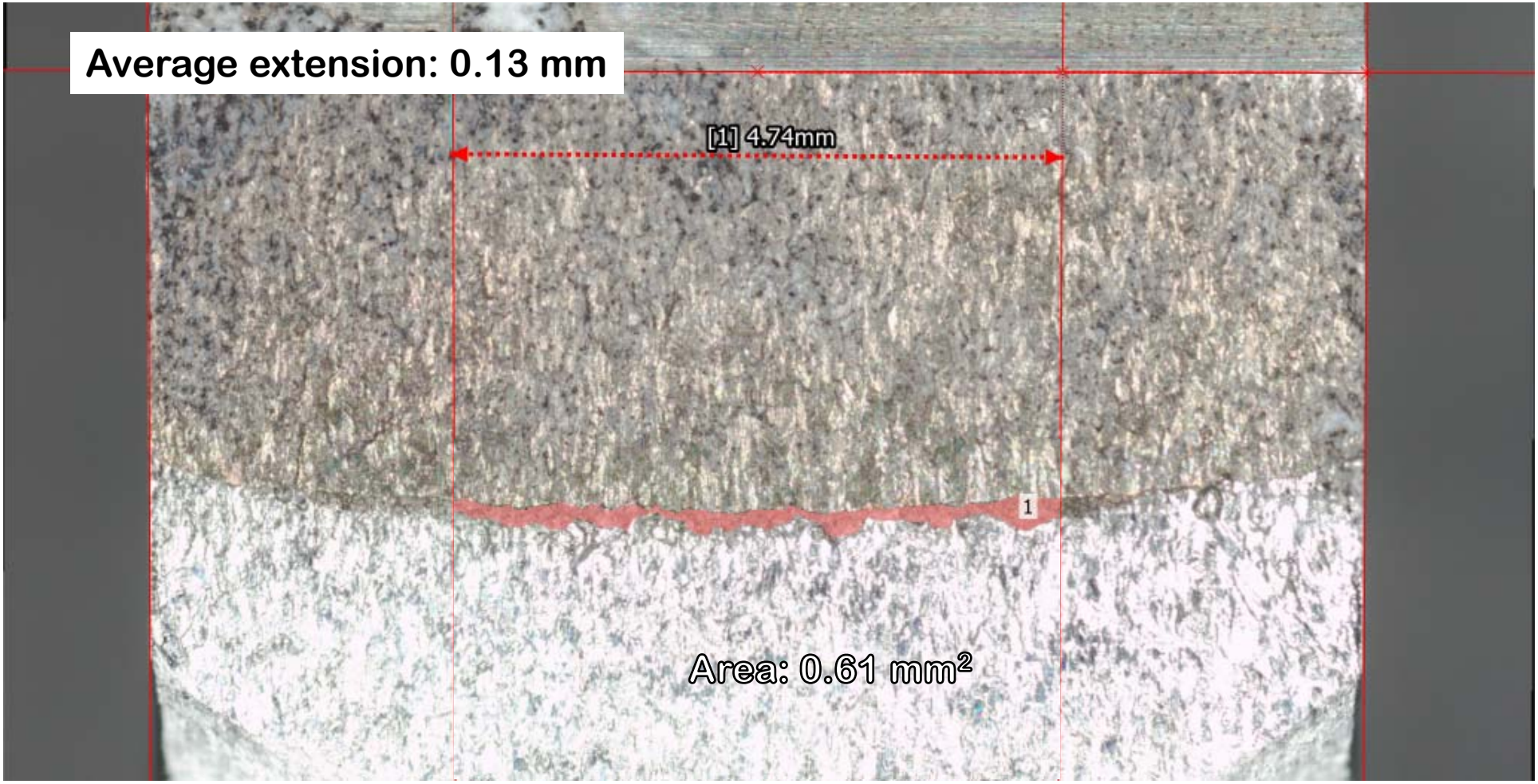


K_{Isi} Method

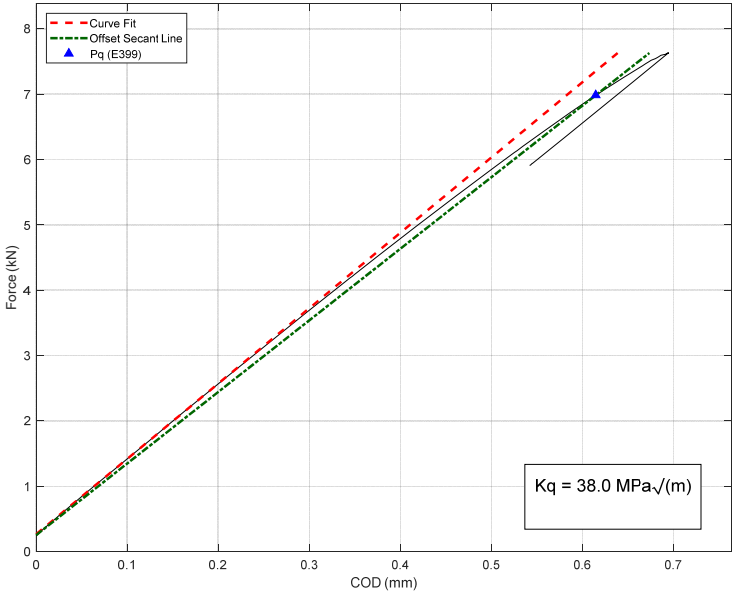
W = 38.1 mm
B = 9.5 mm
B_n = 9.5 mm
a = 19.6 mm
$M_{K,limit}$ (K_{Isi}) = 1.48

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	6.985	38.1	---	2.03	Not Valid
K_{Isi}	7.637	41.7	---	1.70	Valid

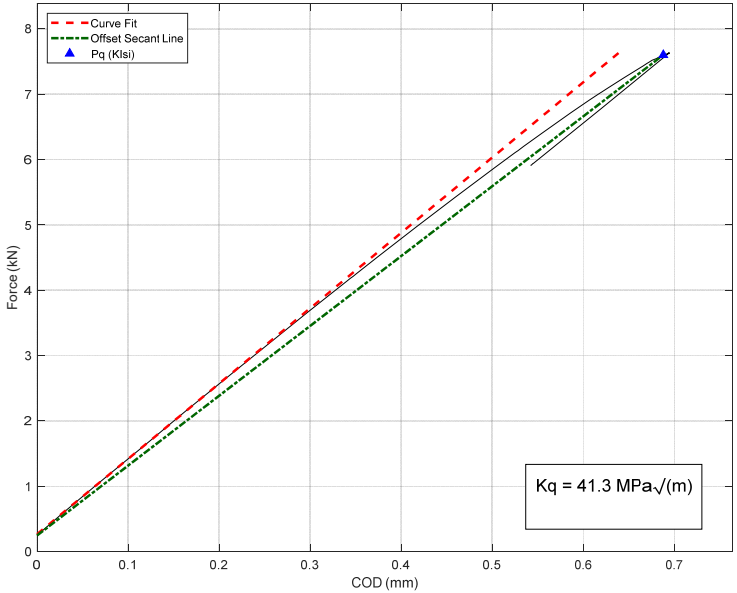
K-1.5-4-7 – Fracture Surface



K-15-4-8 - Interrupted Test



K_{Ic} Method

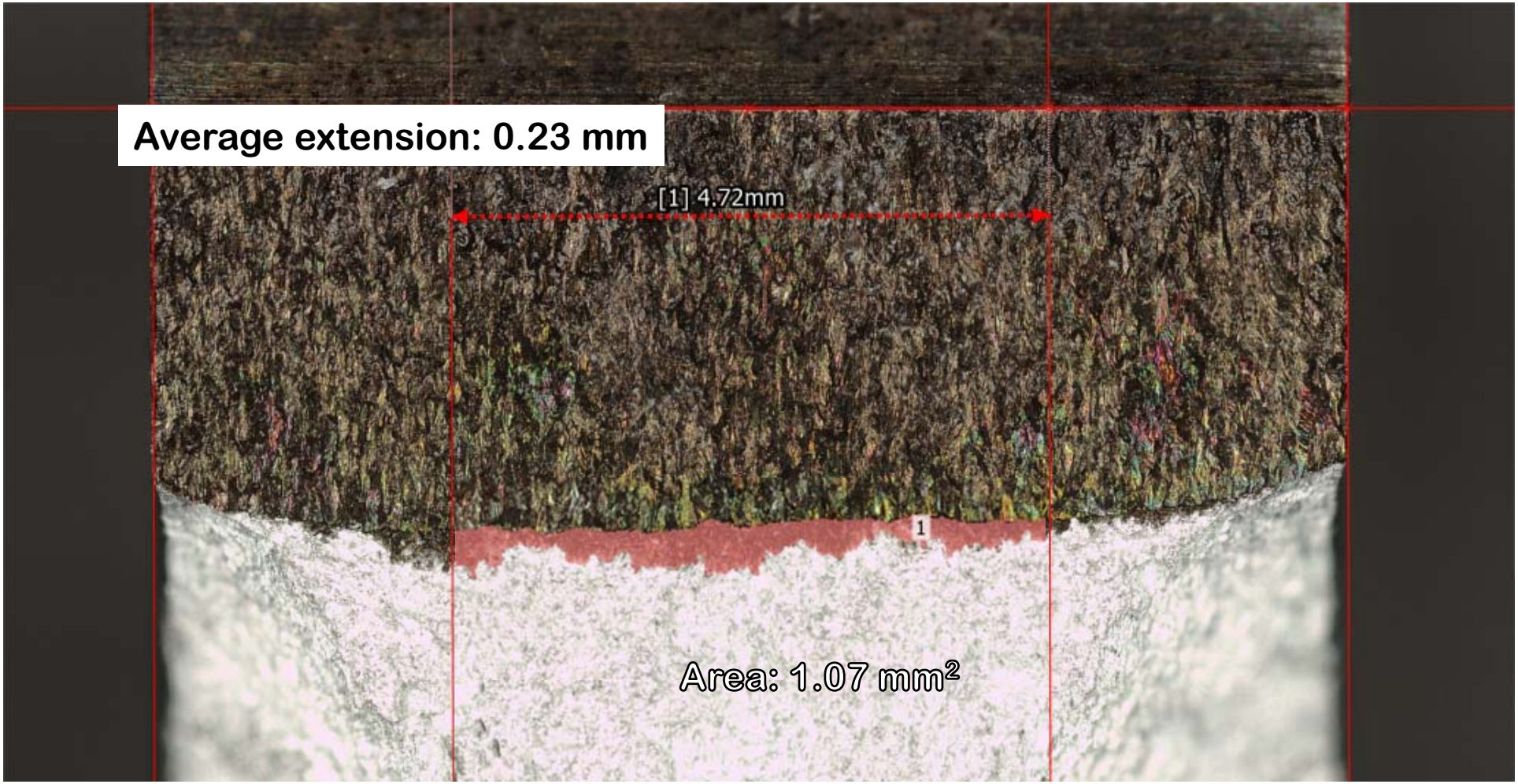


K_{Isi} Method

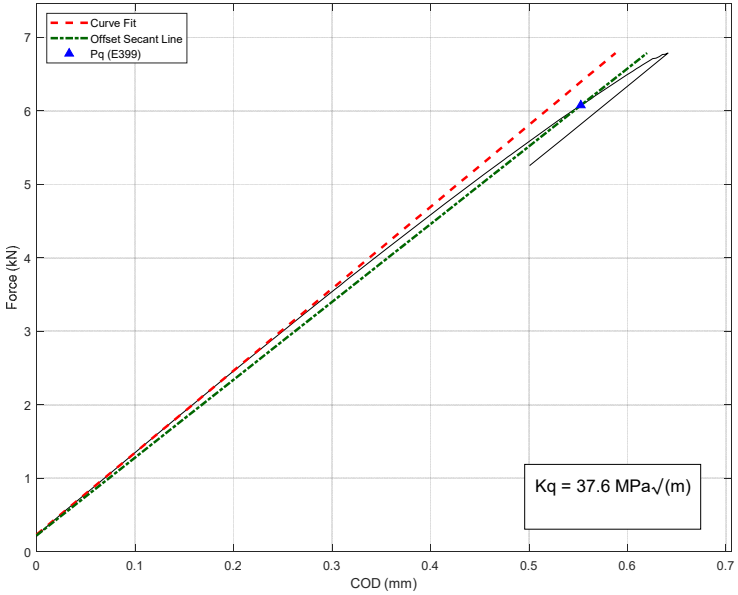
W = 38.1 mm
B = 9.5 mm
B_n = 9.5 mm
a = 19.5 mm
$M_{K,limit}$ (K_{Isi}) = 1.48

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	6.984	38.0	---	2.06	Not Valid
K_{Isi}	7.599	41.3	---	1.74	Valid

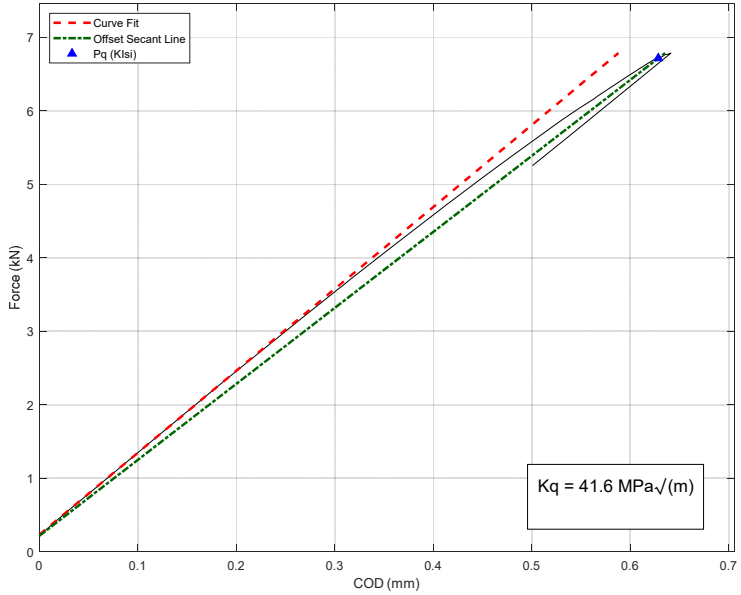
K-1.5-4-8 – Fracture Surface



K-15-4-10 - Interrupted Test



K_{Ic} Method

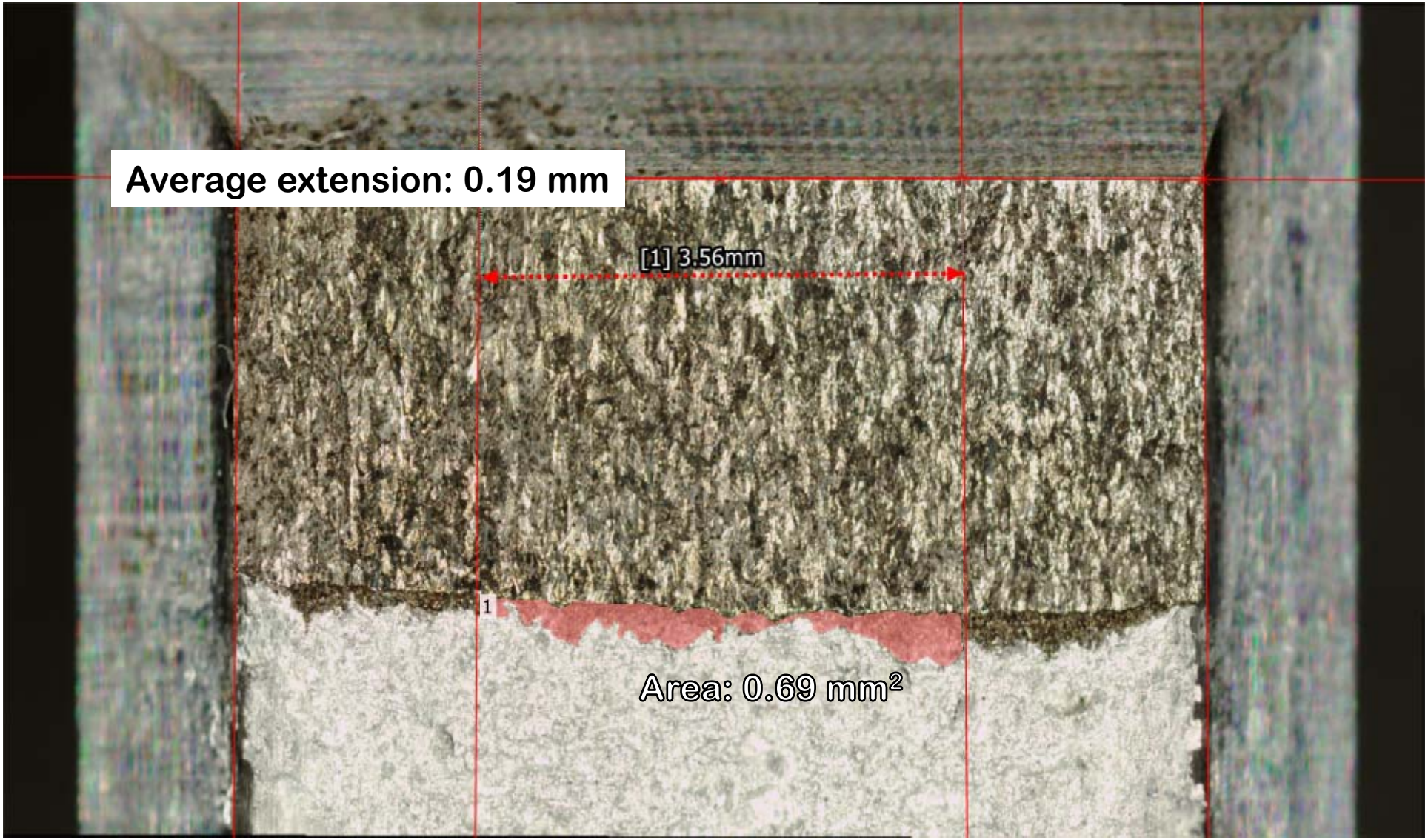


K_{Isi} Method

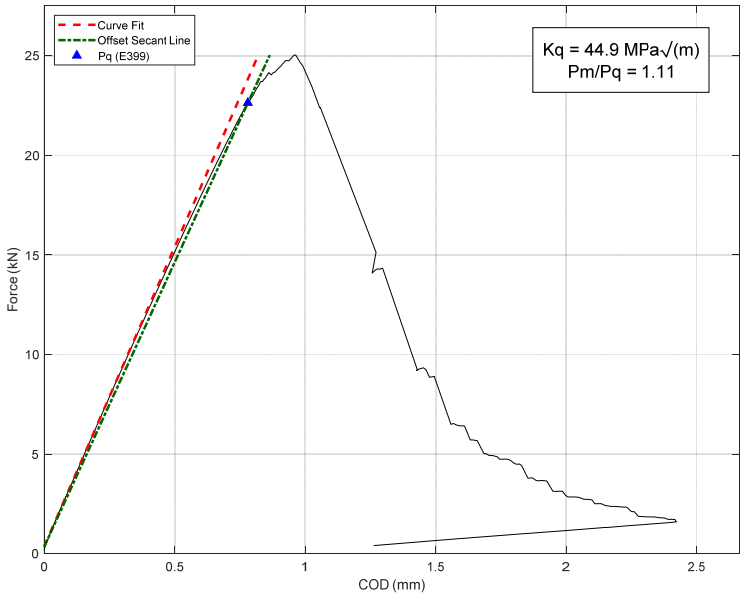
W = 38.1 mm
B = 9.5 mm
B_n = 7.2 mm
a = 19.4 mm
$M_{K,limit}$ (K_{Isi}) = 1.49

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	6.076	37.6	---	2.11	Not Valid
K_{Isi}	6.716	41.6	---	1.73	Valid

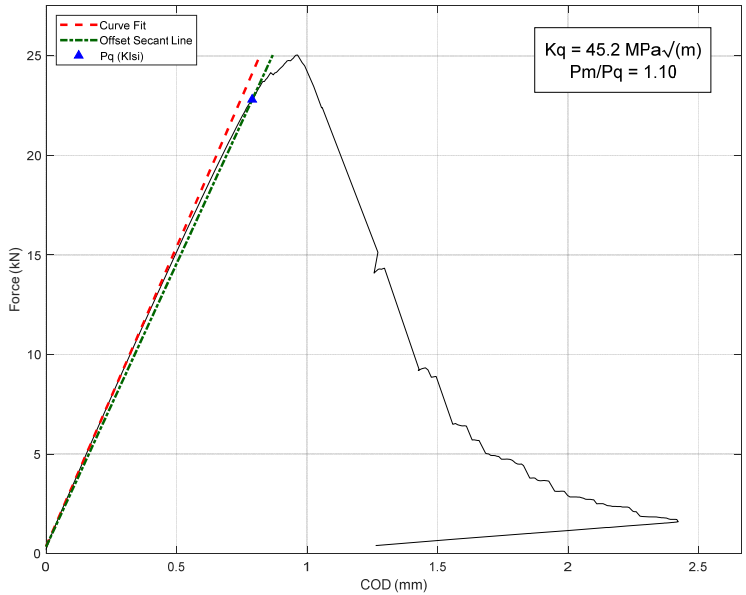
K-1.5-4-10 – Fracture Surface



K-2-2-4 - E399 Test (Side Grooved)



K_{Ic} Method

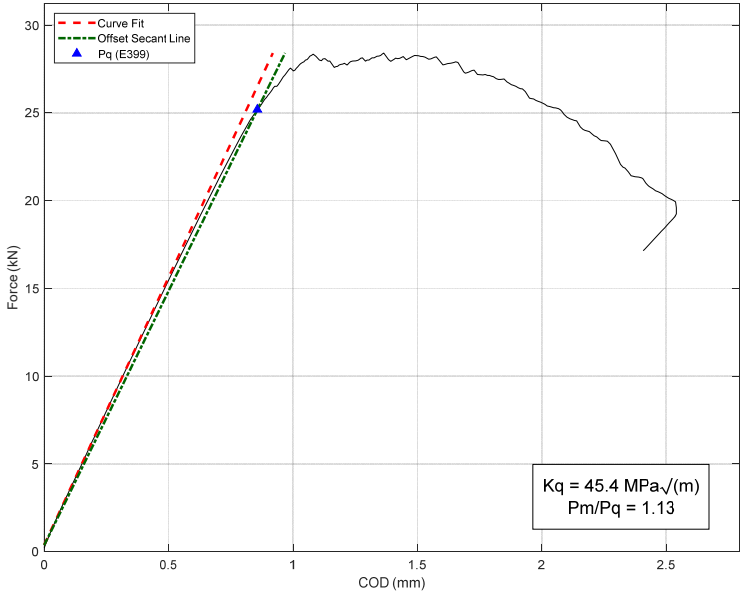


K_{Isi} Method

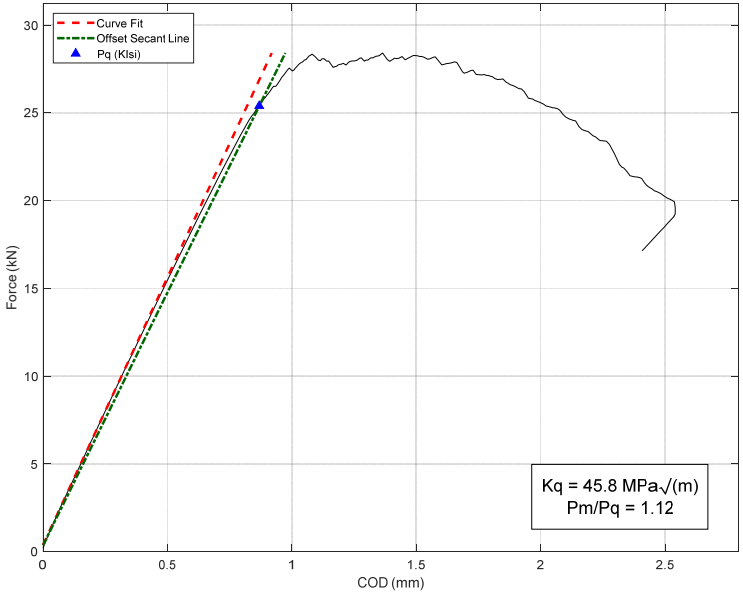
W = 50.8 mm
B = 25.4 mm
B_n = 20.0 mm
a = 26.1 mm
$M_{K,limit}$ (K_{Isi}) = 1.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	22.645	44.9	1.11	1.96	Pm/Pq, Ligament
K_{Isi}	22.800	45.2	1.10	1.94	Ligament

K-2-2-5 - E399 Test



K_{Ic} Method

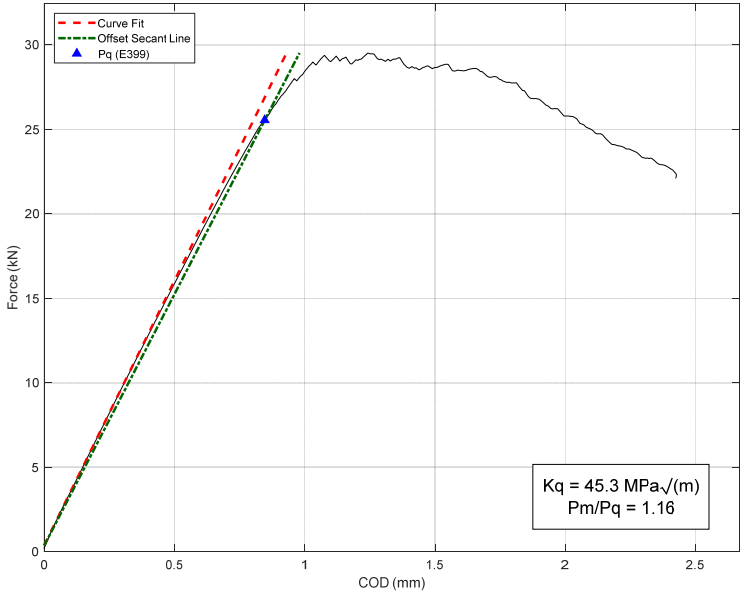


K_{Isi} Method

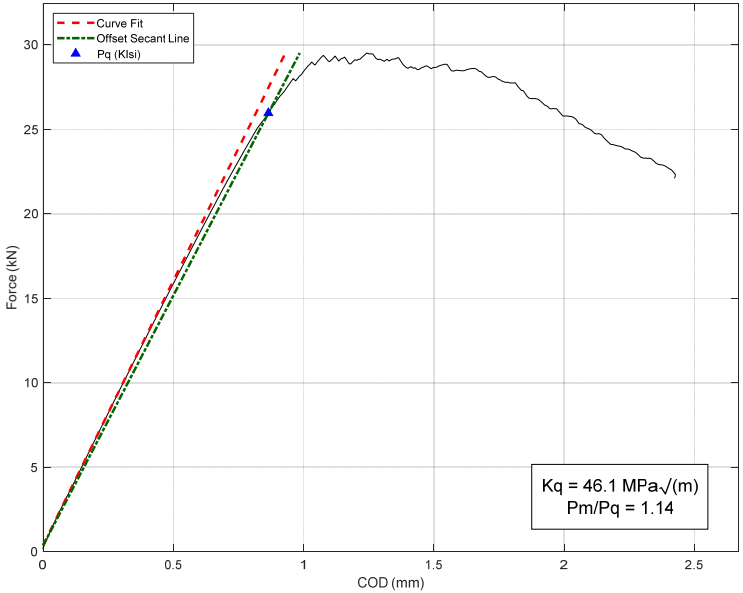
W = 50.8 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.5 mm
$M_{K,limit}$ (K_{Isi}) = 1.95

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	25.182	45.4	1.13	1.89	Pm/Pq, Ligament
K_{Isi}	25.390	45.8	1.12	1.86	Ligament

K-2-2-10 - E399 Test



K_{Ic} Method

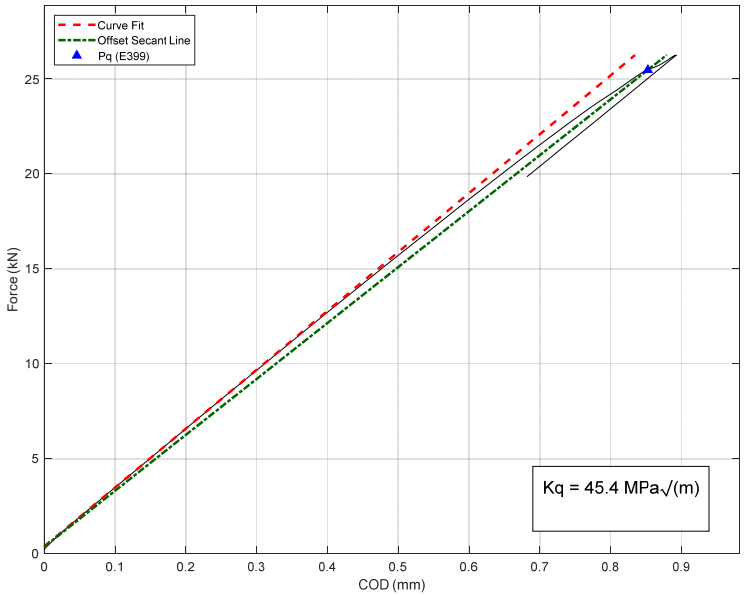


K_{Isi} Method

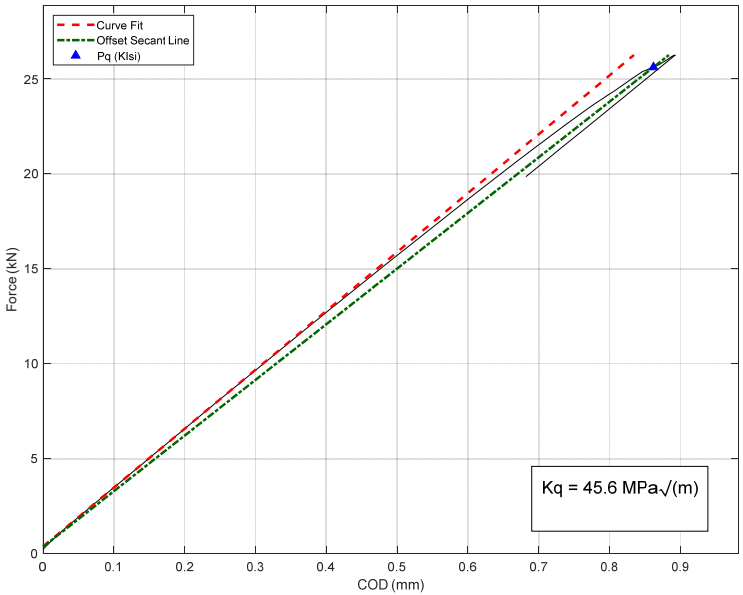
W = 50.8 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.2 mm
$M_{K,limit}$ (K_{Isi}) = 1.97

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	25.547	45.3	1.16	1.92	Pm/Pq, Ligament
K_{Isi}	25.962	46.1	1.14	1.85	Ligament

K-2-2-1 - Interrupted Test



K_{Ic} Method



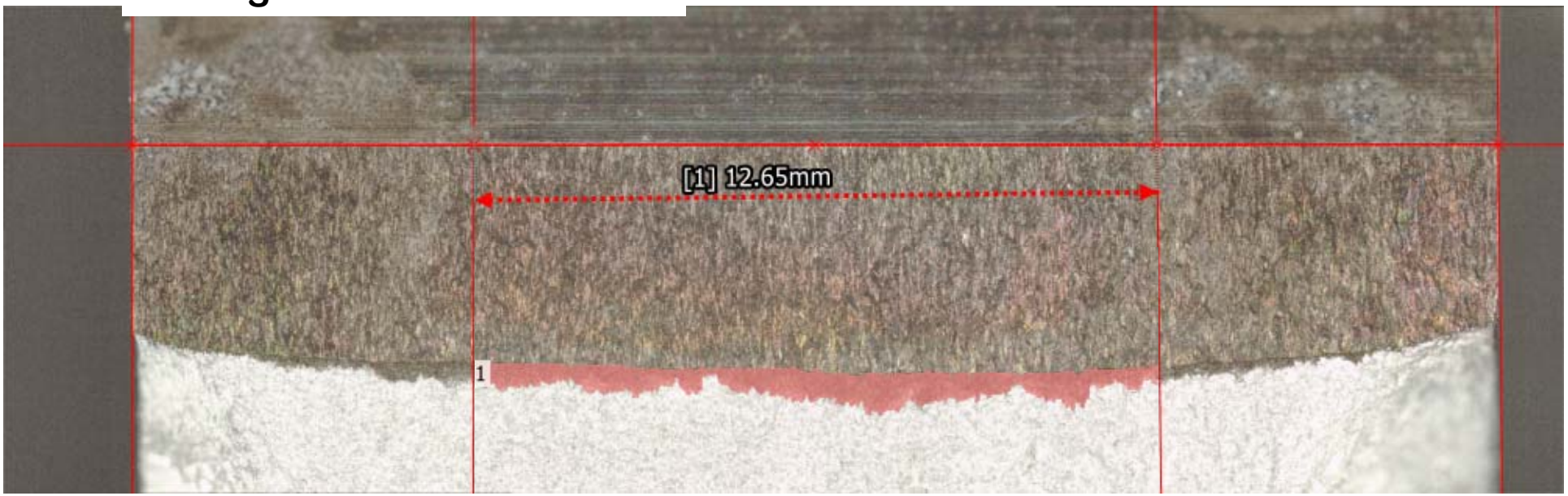
K_{Isi} Method

W = 50.8 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.3 mm
$M_{K,limit}$ (K_{Isi}) = 1.96

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	25.475	45.4	---	1.91	Not Valid
K_{Isi}	25.619	45.6	---	1.88	Not Valid

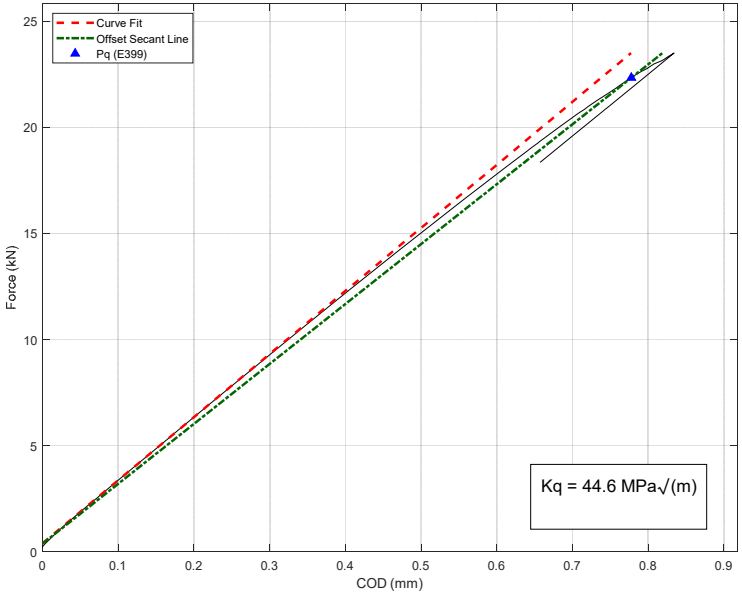
K-2-2-1 – Fracture Surface

Average extension: 0.45 mm

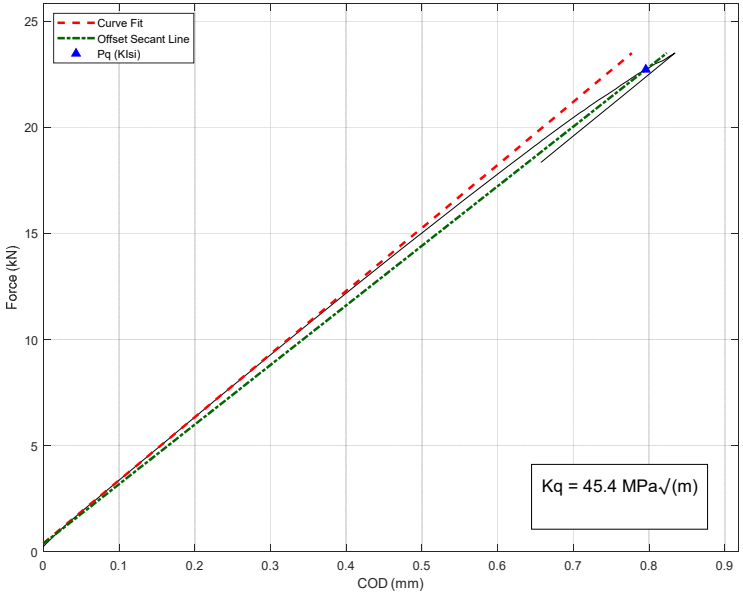


Area: 5.74 mm²

K-2-2-2 - Interrupted Test



K_{Ic} Method

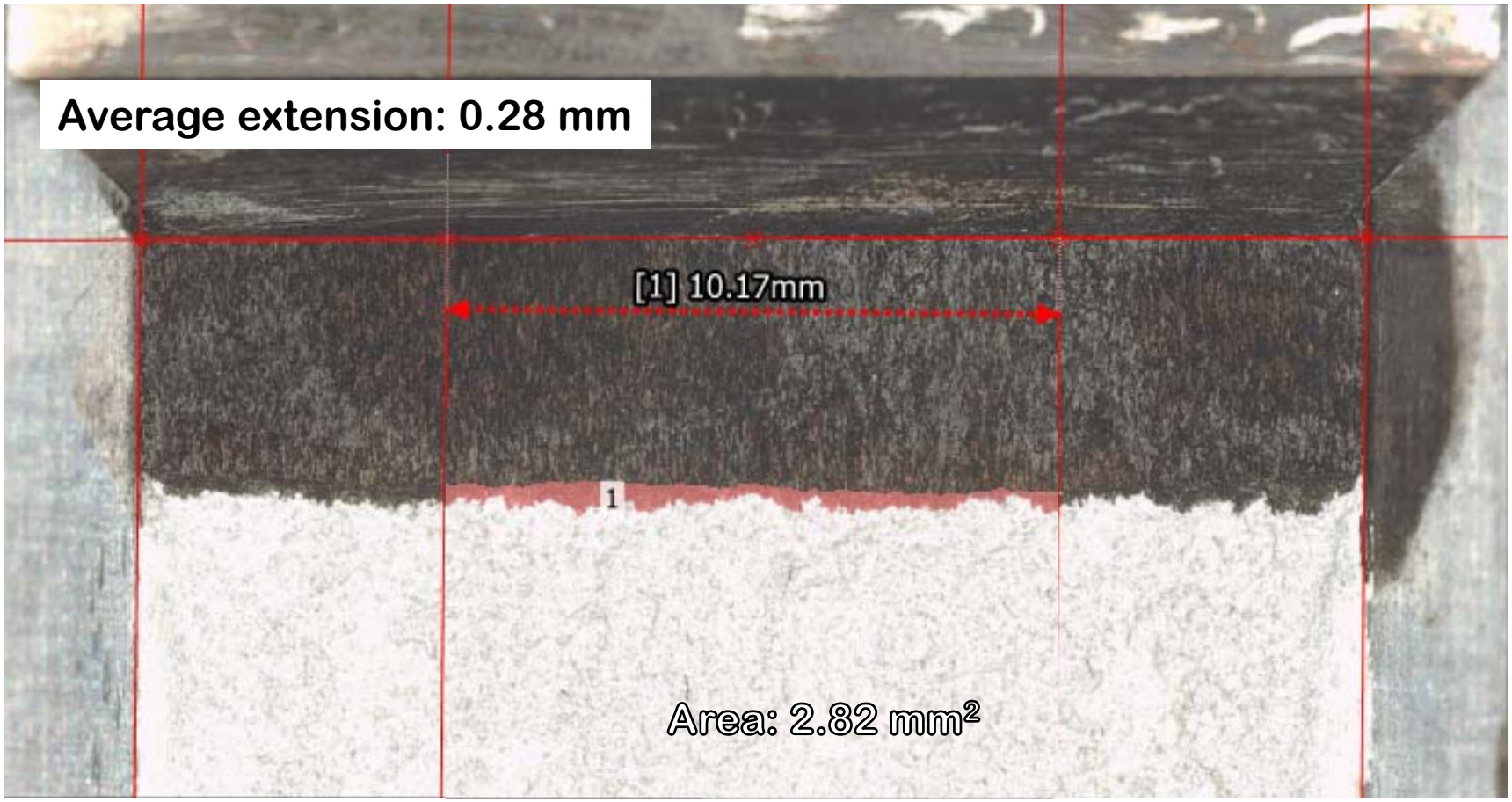


K_{Isi} Method

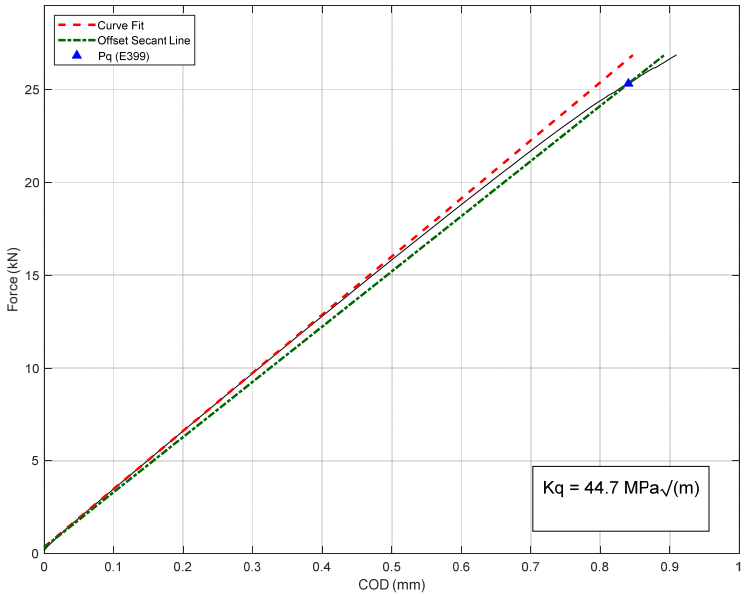
W = 50.8 mm
B = 25.4 mm
B_n = 20.3 mm
a = 26.3 mm
$M_{K,limit}$ (K_{Isi}) = 1.96

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	22.345	44.6	---	1.97	Not Valid
K_{Isi}	22.732	45.4	---	1.90	Not Valid

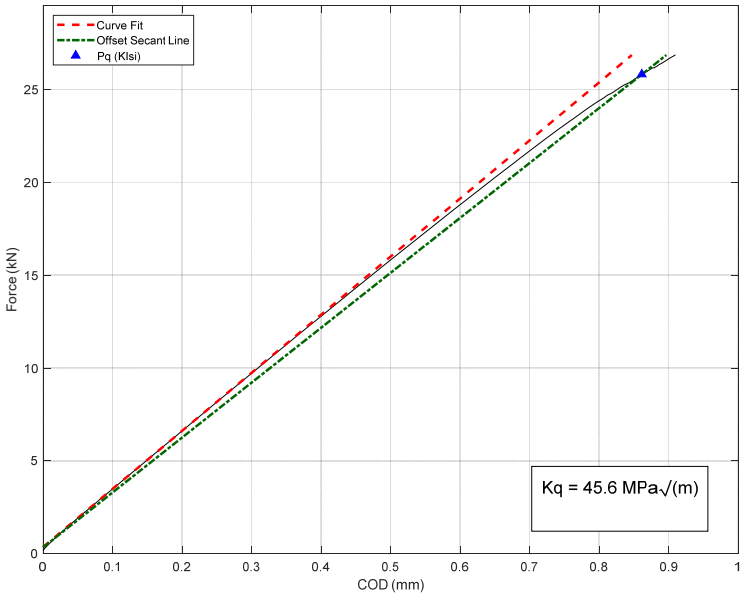
K-2-2-2 – Fracture Surface



K-2-2-8 - Interrupted Test



K_{Ic} Method

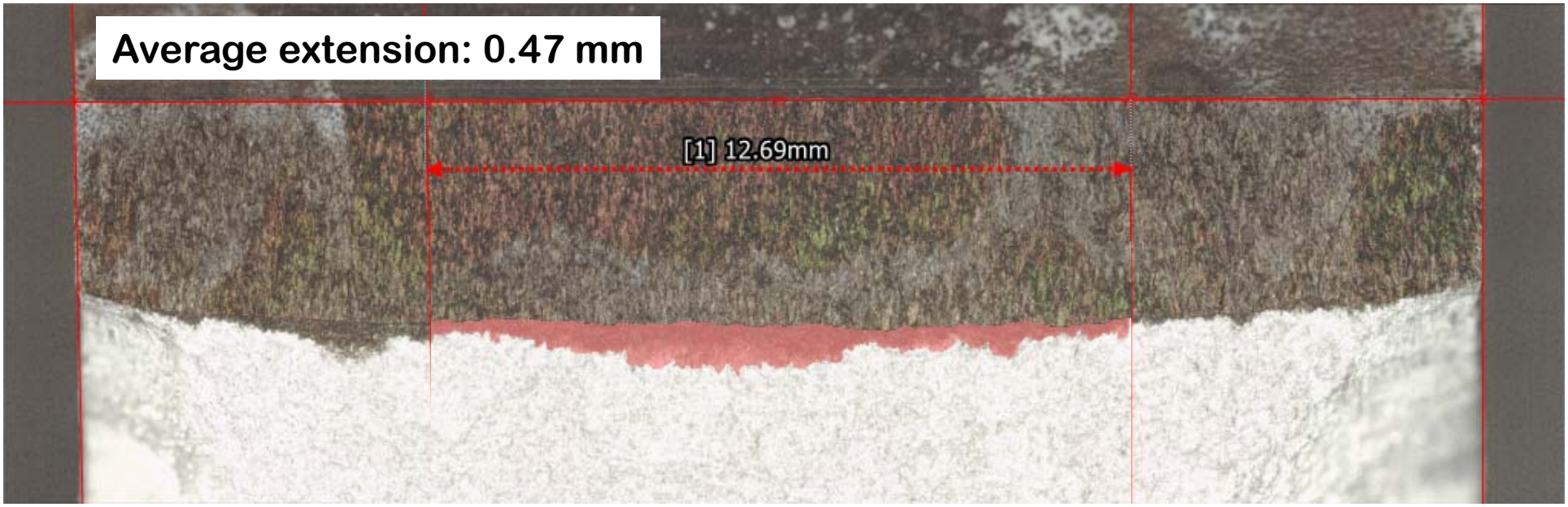


K_{Isi} Method

W = 50.9 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.2 mm
$M_{K,limit}$ (K_{Isi}) = 1.98

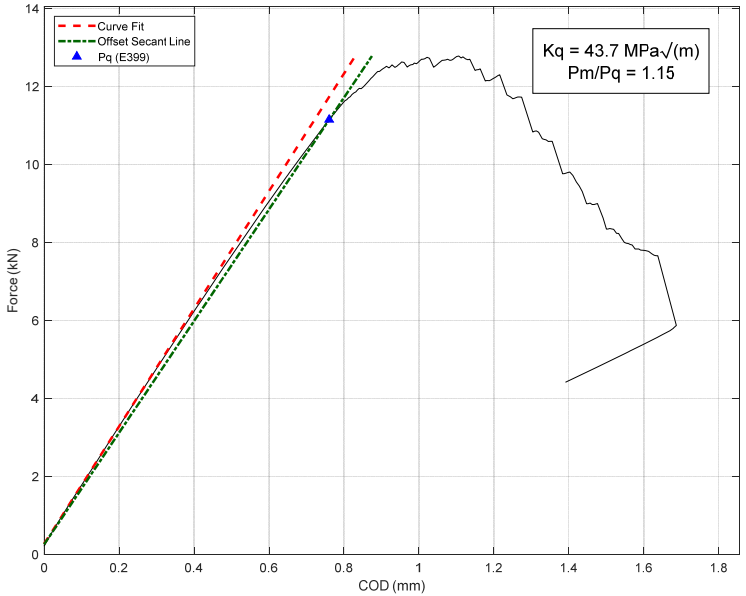
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	25.323	44.7	---	1.98	Not Valid
K_{Isi}	25.824	45.6	---	1.90	Not Valid

K-2-2-8 – Fracture Surface

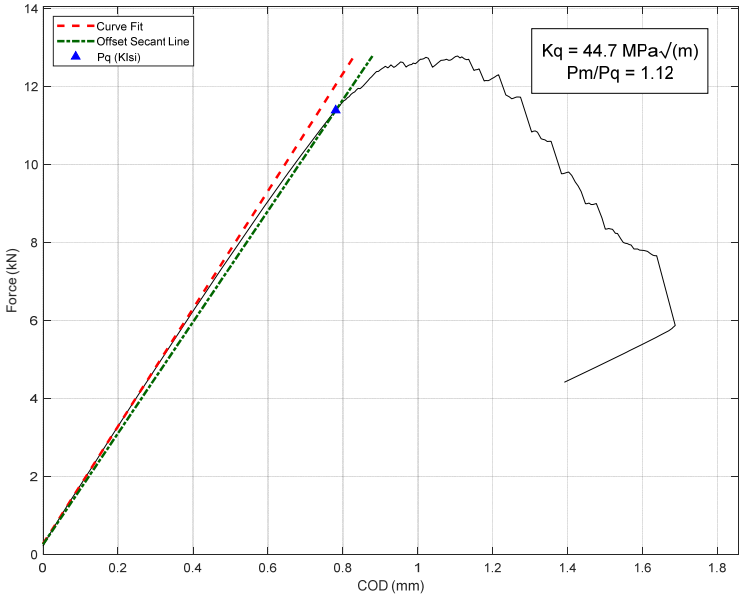


Area: 5.94 mm²

K-2-4-4 - E399 Test (Side Grooved)



K_{Ic} Method

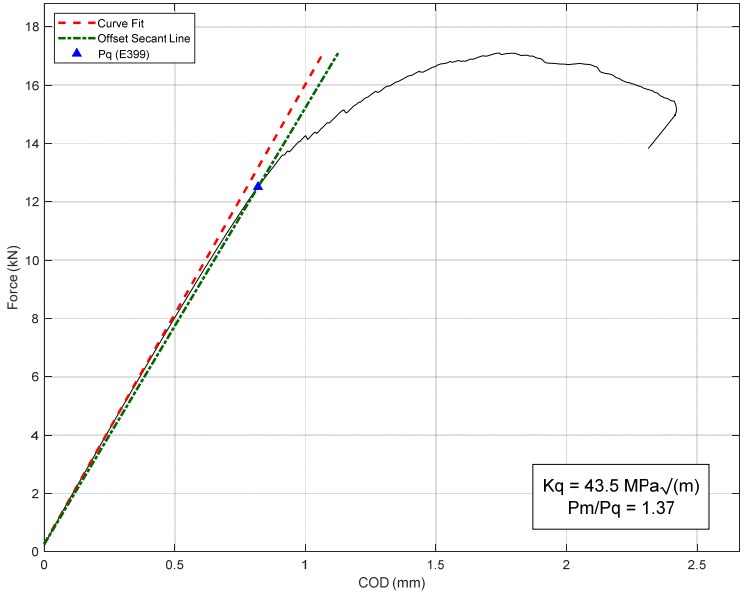


K_{Isi} Method

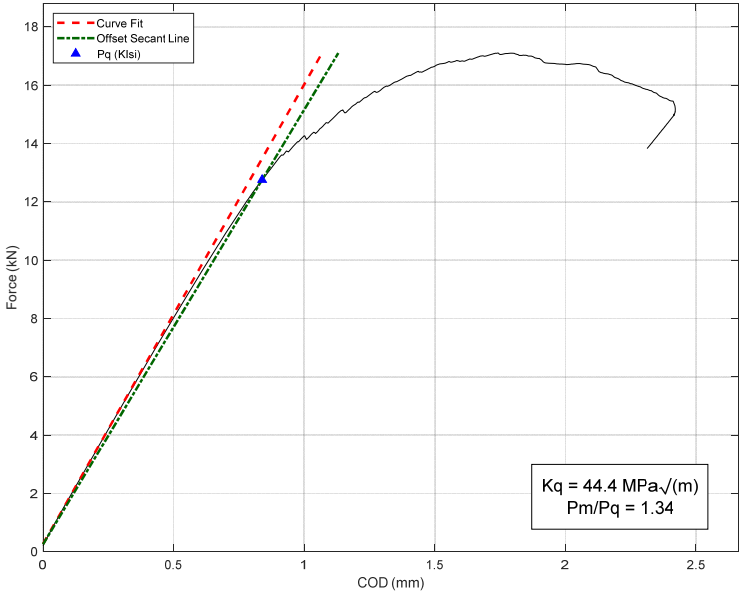
W = 50.9 mm
B = 12.7 mm
B_n = 10.1 mm
a = 26.0 mm
$M_{K,limit}$ (K_{Isi}) = 1.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	11.152	43.7	1.15	2.08	Pm/Pq, Ligament
K_{Isi}	11.392	44.7	1.12	1.99	Valid

K-2-4-7 - E399 Test



K_{Ic} Method

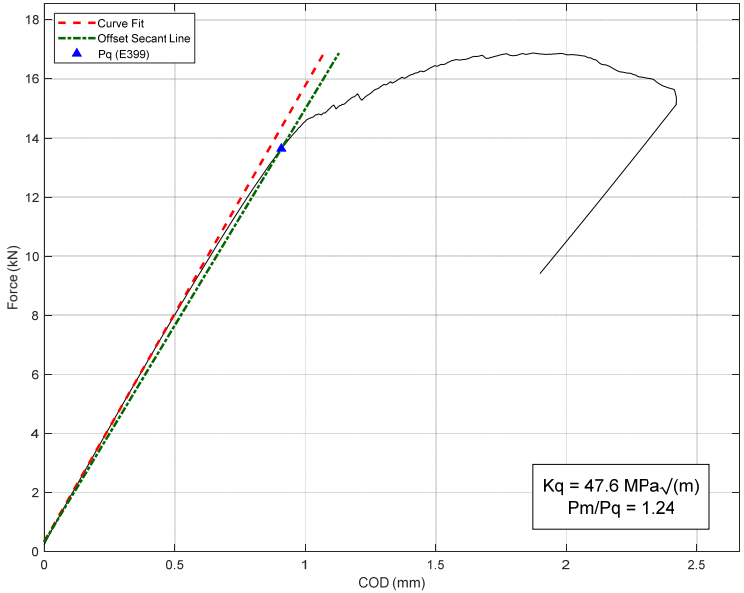


K_{Isi} Method

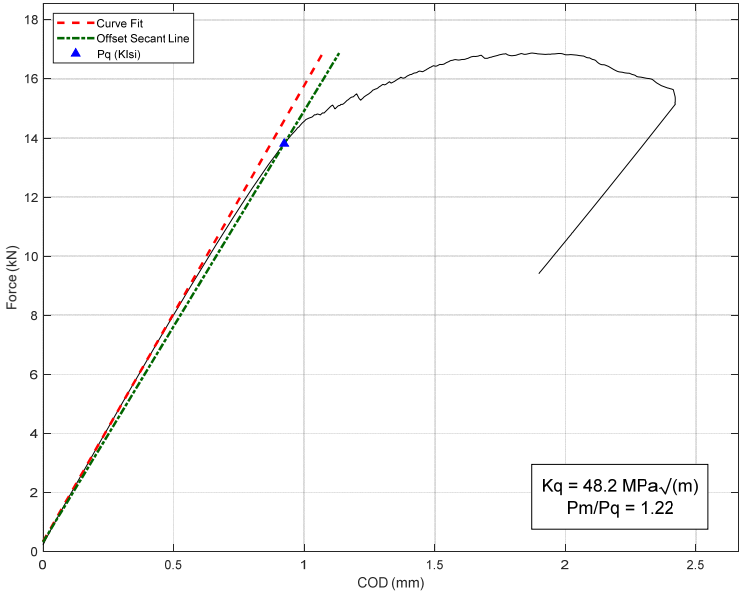
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 25.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.00

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	12.512	43.5	1.37	2.11	Pm/Pq, Ligament
K_{Isi}	12.758	44.4	1.34	2.03	Valid

K-2-4-10 - E399 Test



K_{Ic} Method

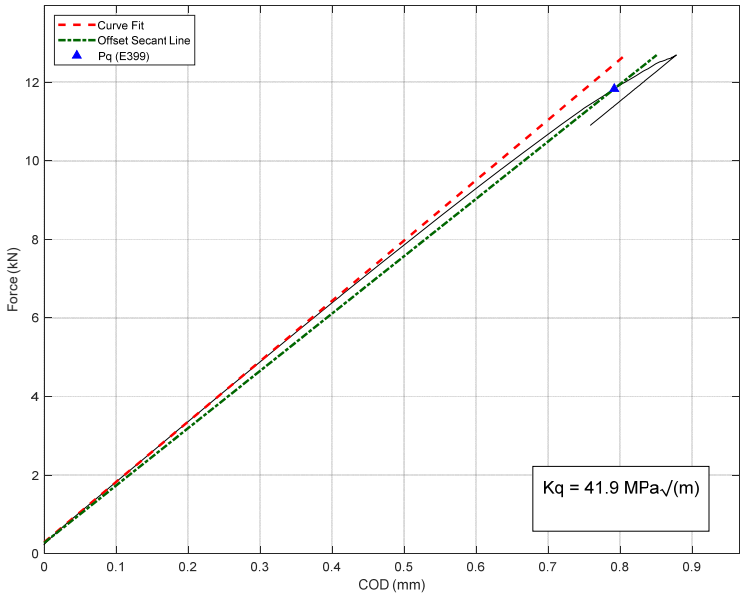


K_{Isi} Method

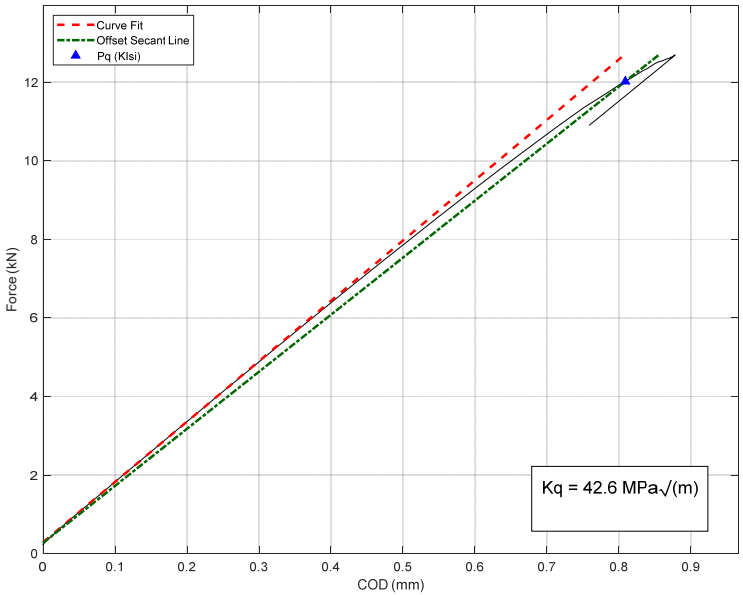
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 25.9 mm
$M_{K,limit}$ (K_{Isi}) = 1.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	13.640	47.6	1.24	1.76	Pm/Pq, Ligament
K_{Isi}	13.809	48.2	1.22	1.72	Ligament

K-2-4-6 - Interrupted Test



K_{Ic} Method

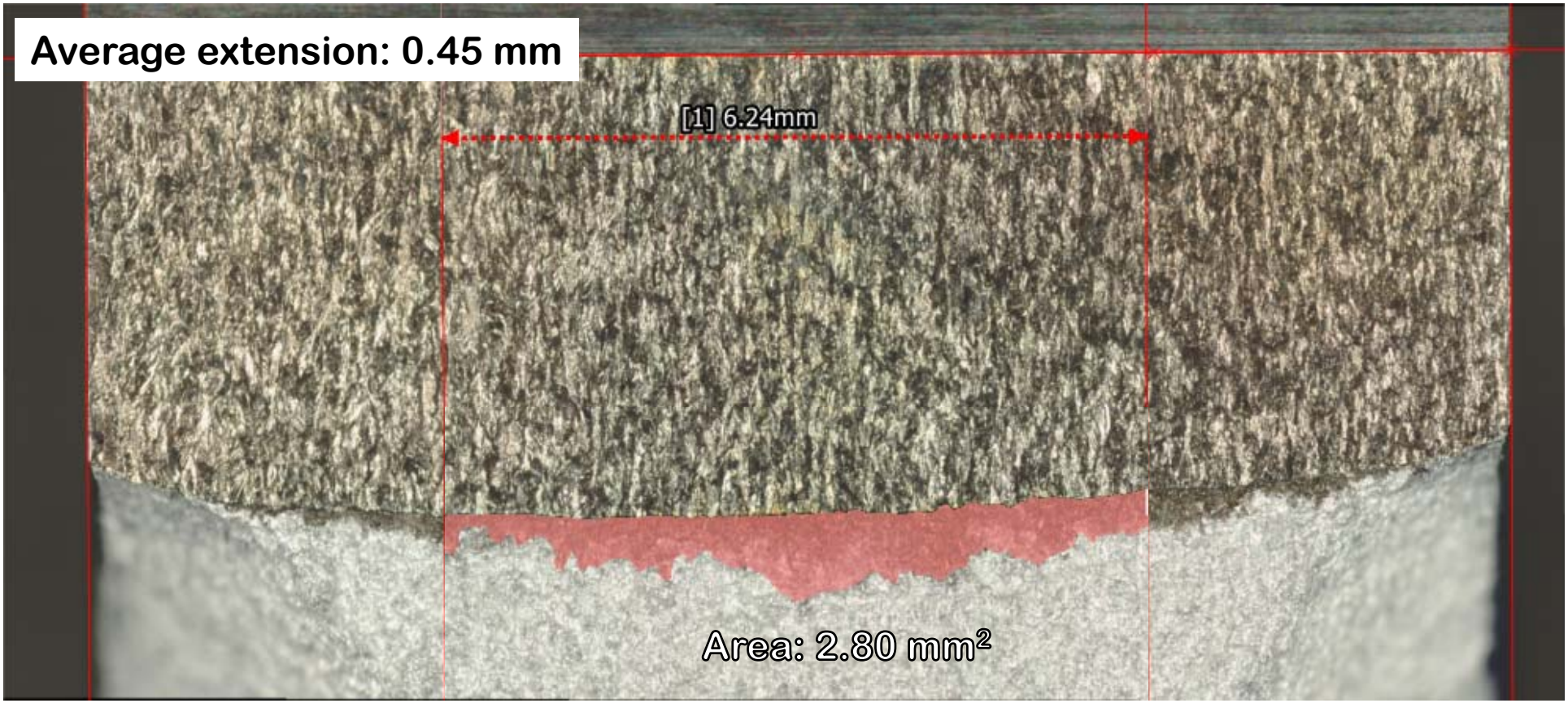


K_{Isi} Method

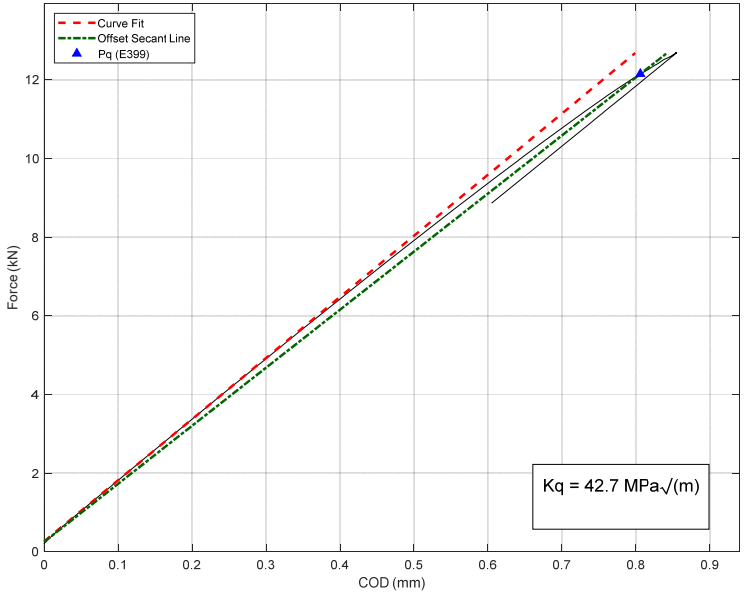
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 26.1 mm
$M_{K,limit}$ (K_{Isi}) = 1.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	11.833	41.9	---	2.25	Not Valid
K_{Isi}	12.021	42.6	---	2.18	Valid

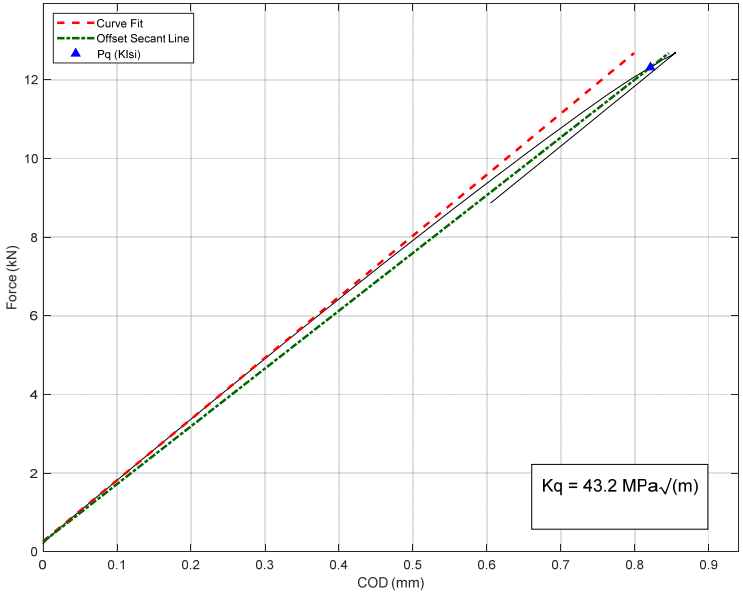
K-2-4-6 – Fracture Surface



K-2-4-8 - Interrupted Test



K_{Ic} Method

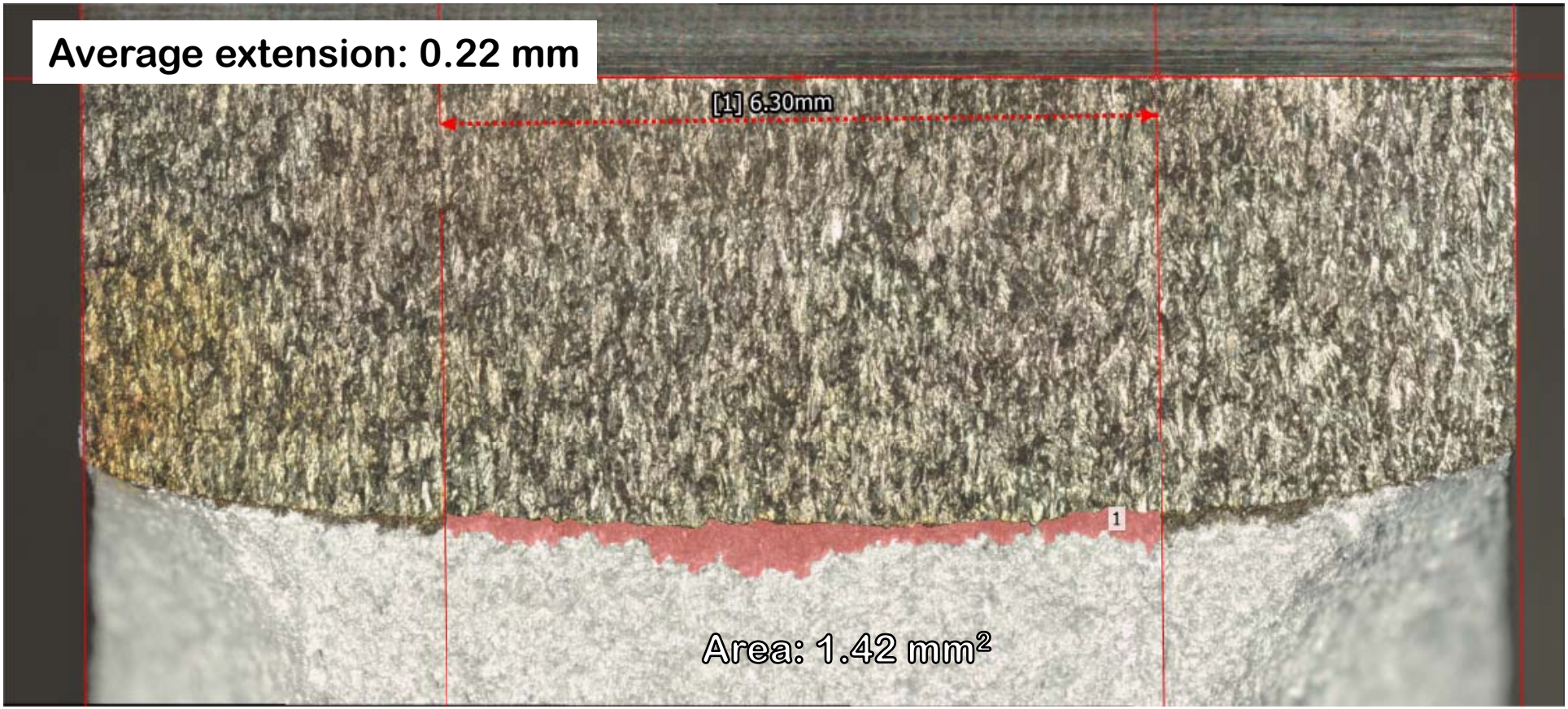


K_{Isi} Method

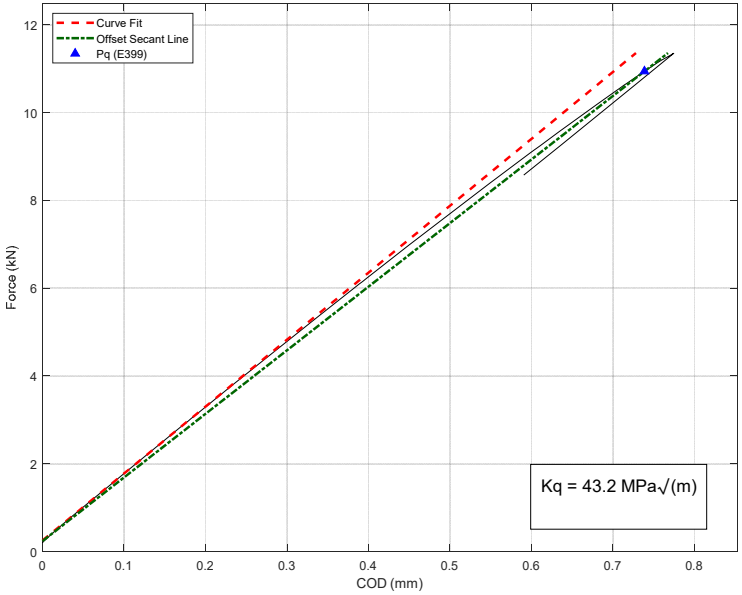
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 26.0 mm
$M_{K,limit}$ (K_{Isi}) = 1.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	12.150	42.7	---	2.18	Not Valid
K_{Isi}	12.316	43.2	---	2.12	Valid

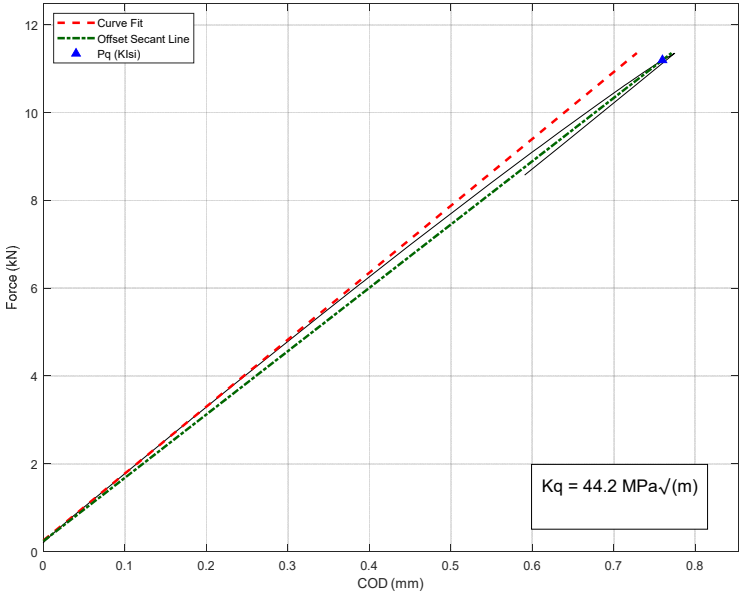
K-2-4-8 – Fracture Surface



K-2-4-9 - Interrupted Test



K_{Ic} Method

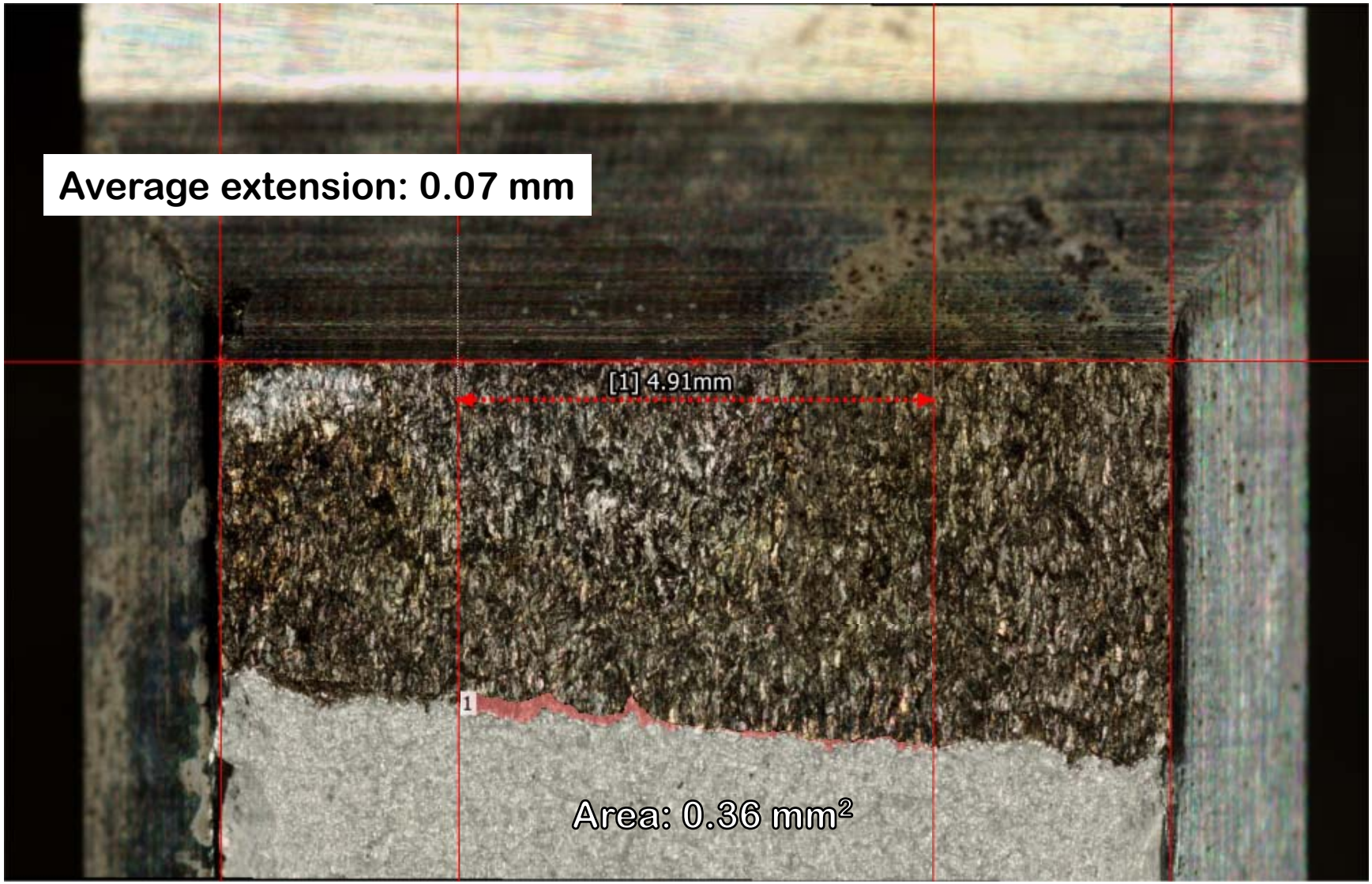


K_{Isi} Method

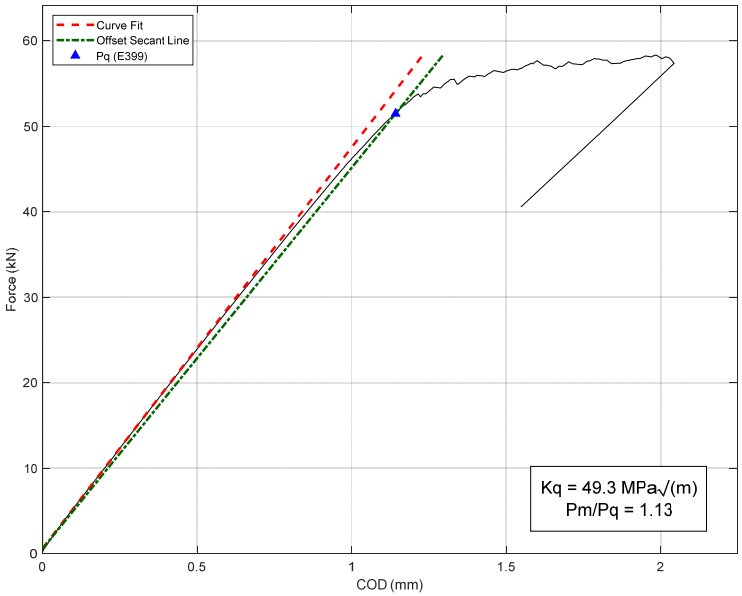
W = 50.8 mm
B = 12.6 mm
B_n = 9.8 mm
a = 25.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.00

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	10.938	43.2	---	2.14	Not Valid
K_{Isi}	11.193	44.2	---	2.04	Valid

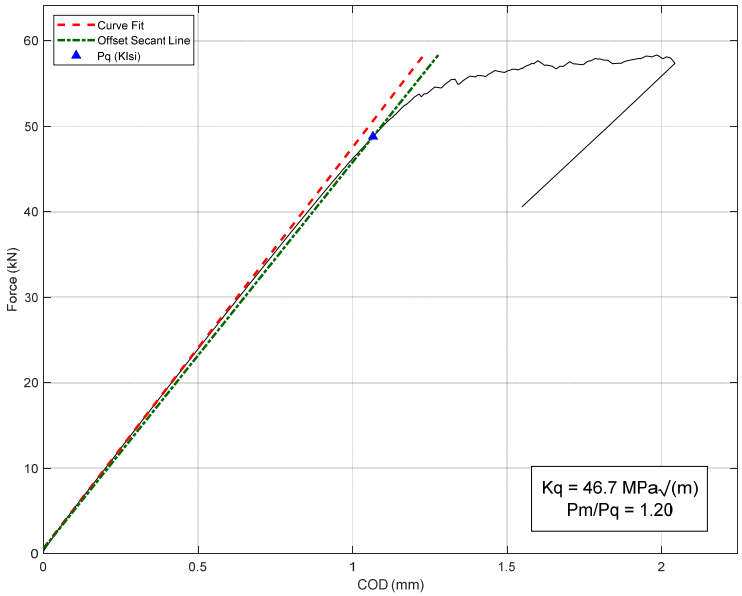
K-2-4-9 – Fracture Surface



K-3-2-1 - E399 Test



K_{Ic} Method

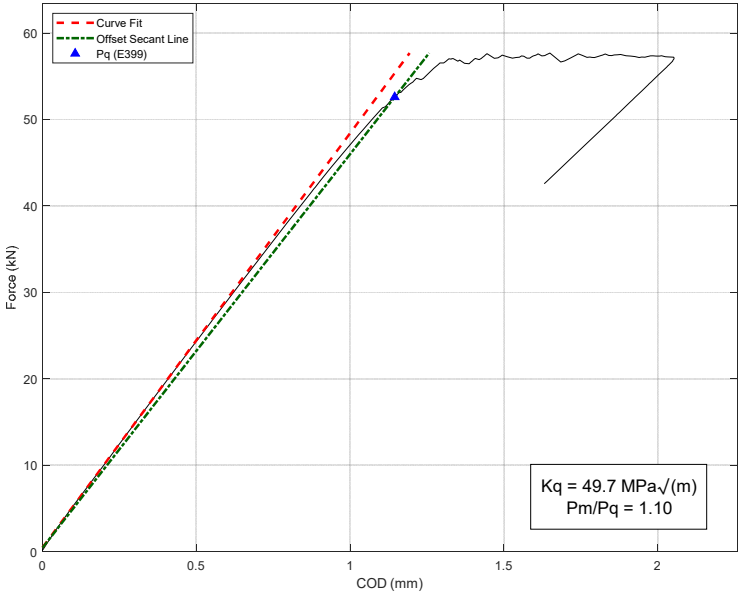


K_{Isi} Method

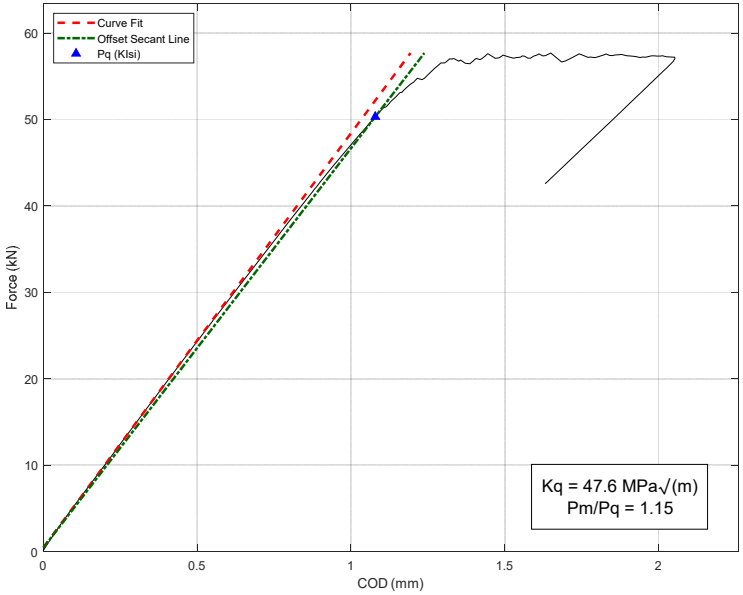
W = 76.2 mm
B = 38.1 mm
B_n = 38.1 mm
a = 39.1 mm
$M_{K,limit}$ (K_{Isi}) = 2.97

	P_q (kN)	**K_q (MPa√m)**	**P_{max}/P_q**	**M_K @ K_q**	**Validity**
K_{Ic}	51.491	49.3	1.13	2.44	Pm/Pq, Ligament
K_{Isi}	48.804	46.7	1.20	2.72	Ligament

K-3-2-4 - E399 Test



K_{Ic} Method

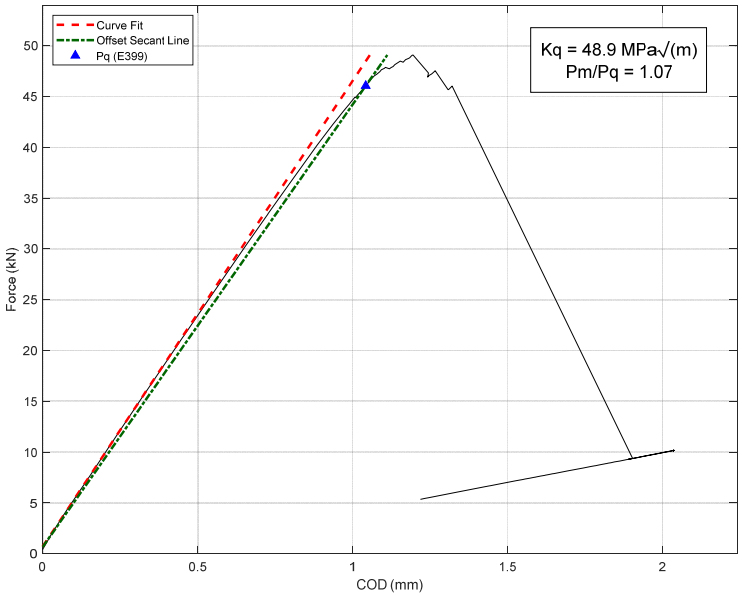


K_{Isi} Method

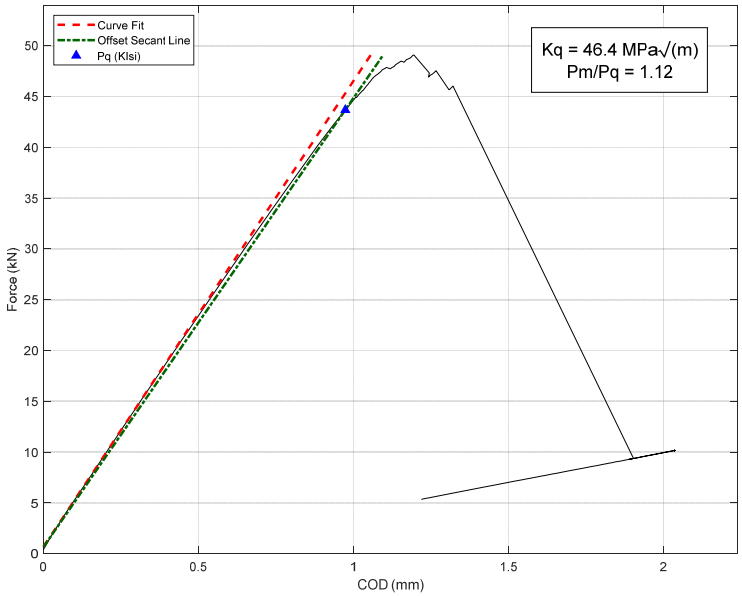
W = 76.3 mm
B = 38.1 mm
B_n = 38.1 mm
a = 38.8 mm
$M_{K,limit}$ (K_{Isi}) = 3.00

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	52.591	49.7	1.10	2.42	Ligament
K_{Isi}	50.317	47.6	1.15	2.65	Ligament

K-3-2-10 - E399 Test (Side Grooved)



K_{Ic} Method

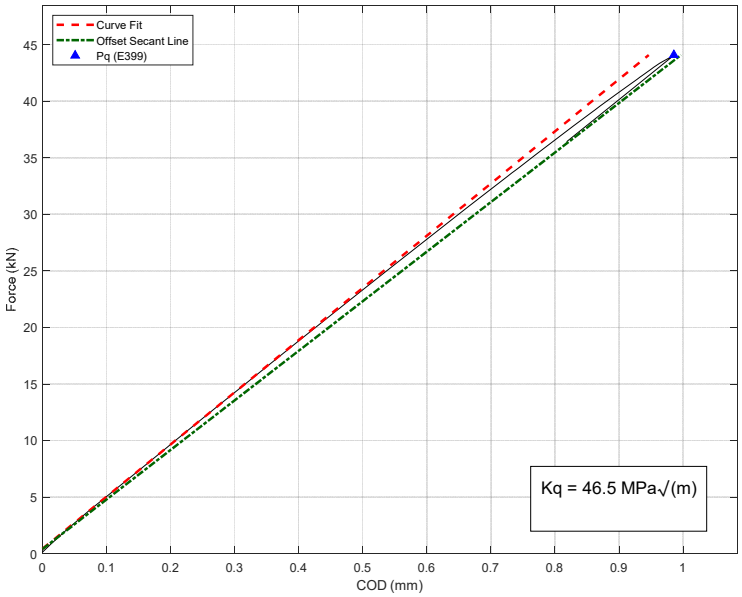


K_{Isi} Method

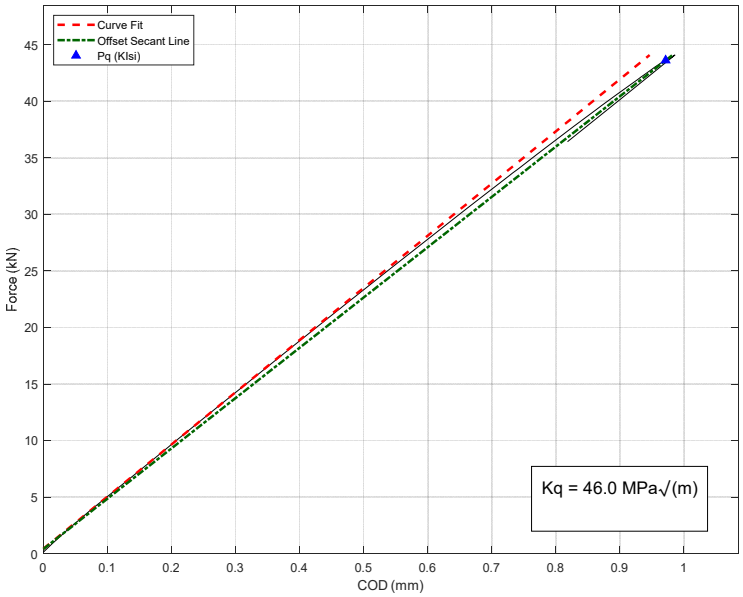
W = 76.2 mm
B = 38.1 mm
B_n = 30.5 mm
a = 38.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	46.072	48.9	1.07	2.50	Ligament
K_{Isi}	43.694	46.4	1.12	2.78	Ligament

K-3-2-2 - Interrupted Test



K_{Ic} Method



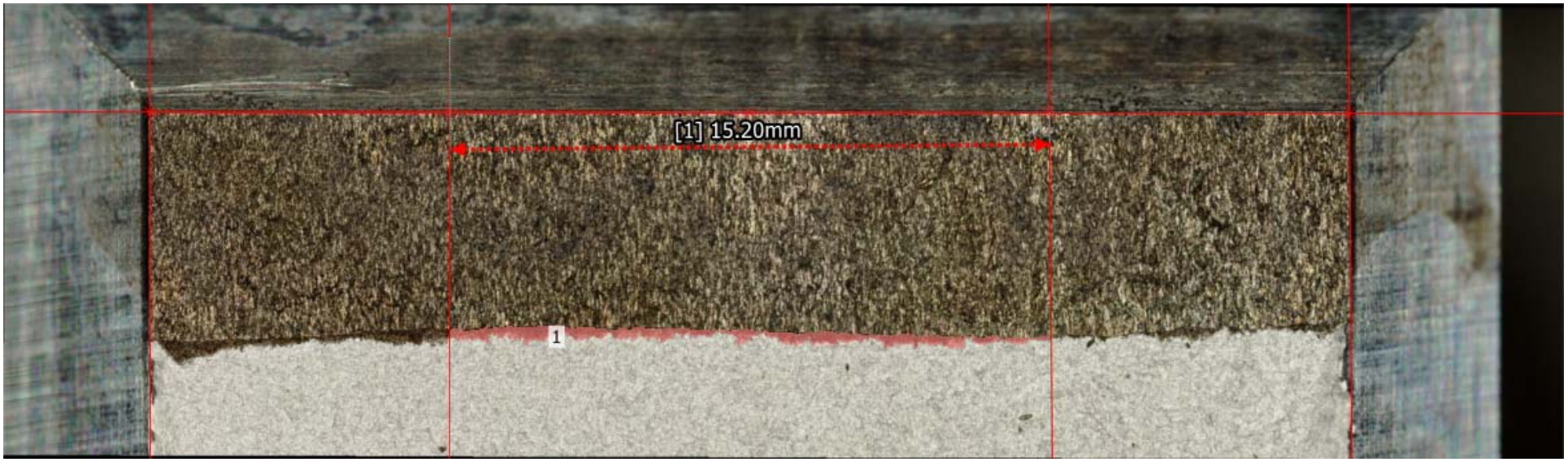
K_{Isi} Method

W = 76.2 mm
B = 38.1 mm
B_n = 30.4 mm
a = 38.7 mm
$M_{K,limit}$ (K_{Isi}) = 3.00

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	44.078	46.5	---	2.78	Valid
K_{Isi}	43.603	46.0	---	2.84	Not Valid

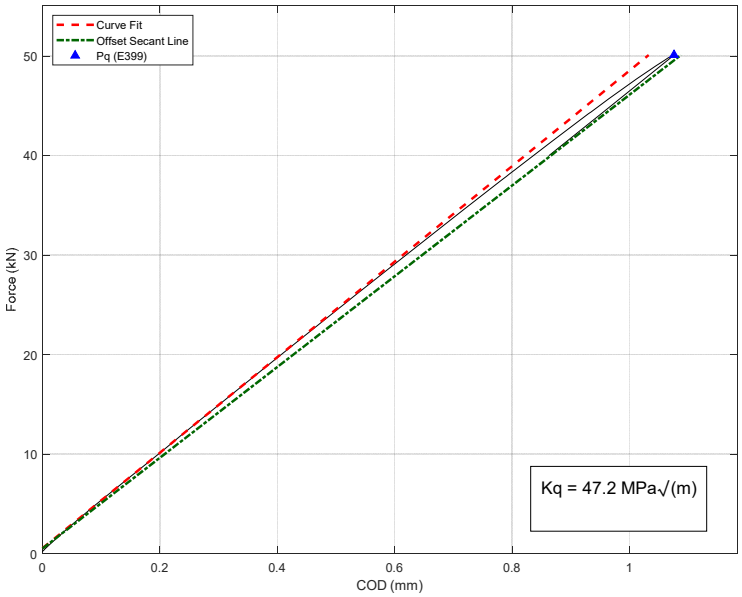
K-3-2-2 – Fracture Surface

Average extension: 0.22 mm

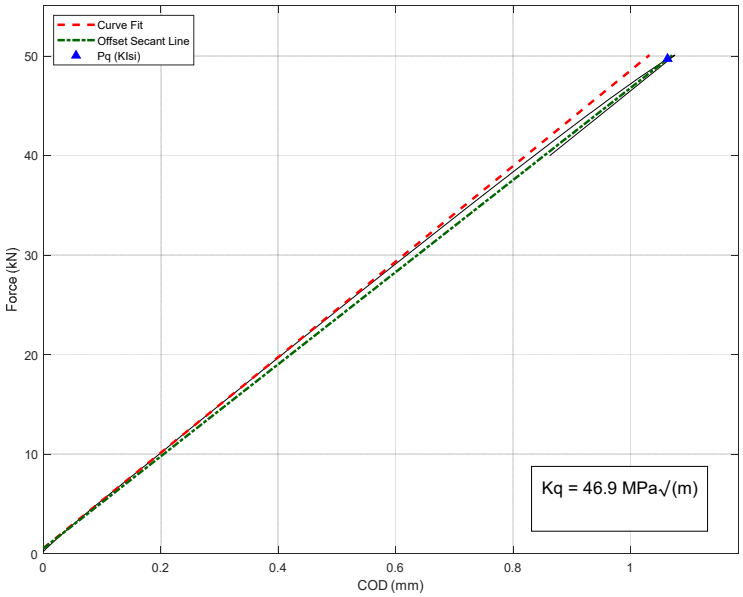


Area: 3.33 mm²

K-3-2-6 - Interrupted Test



K_{Ic} Method



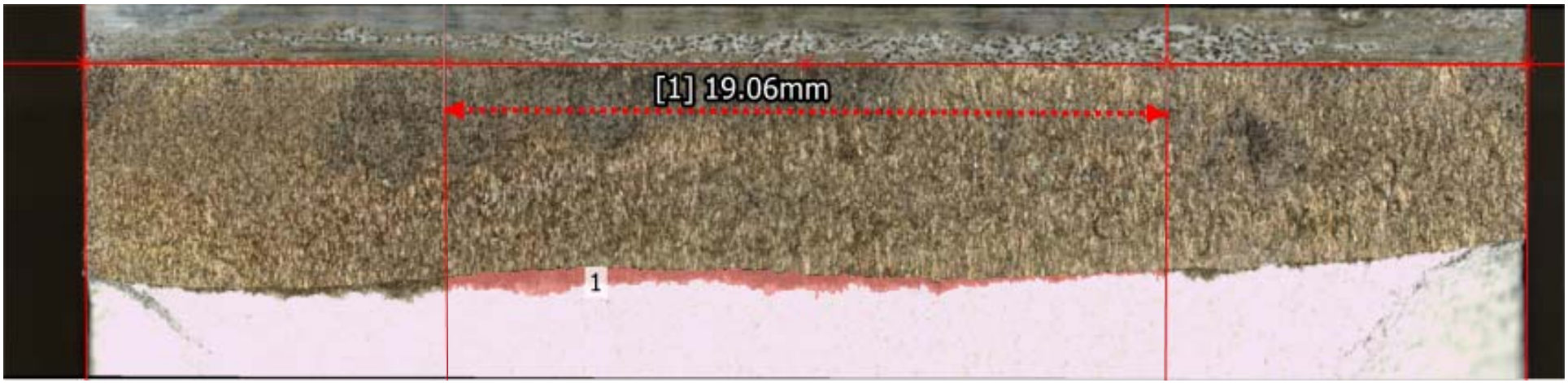
K_{Isi} Method

W = 76.2 mm
B = 38.1 mm
B_n = 38.1 mm
a = 38.7 mm
$M_{K,limit}$ (K_{Isi}) = 3.00

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	50.097	47.2	---	2.69	Valid
K_{Isi}	49.715	46.9	---	2.73	Not Valid

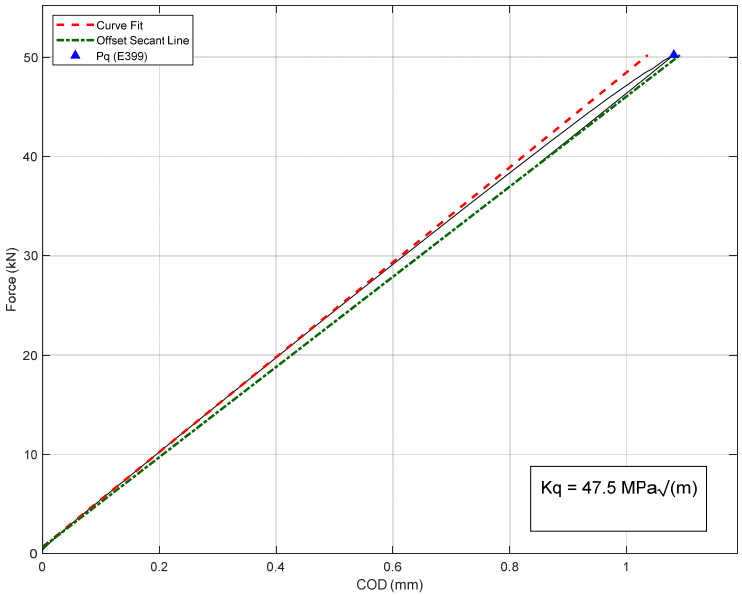
K-3-2-6 – Fracture Surface

Average extension: 0.33 mm

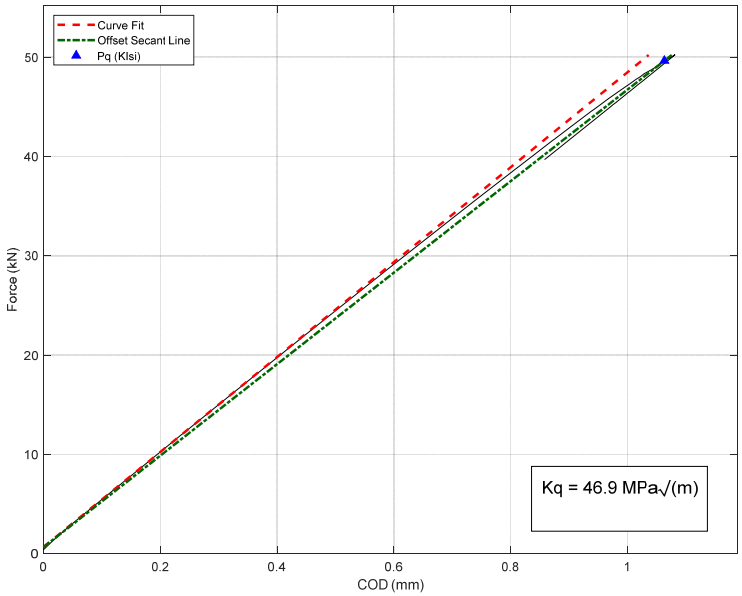


Area: 6.25 mm^2

K-3-2-7 - Interrupted Test



K_{Ic} Method



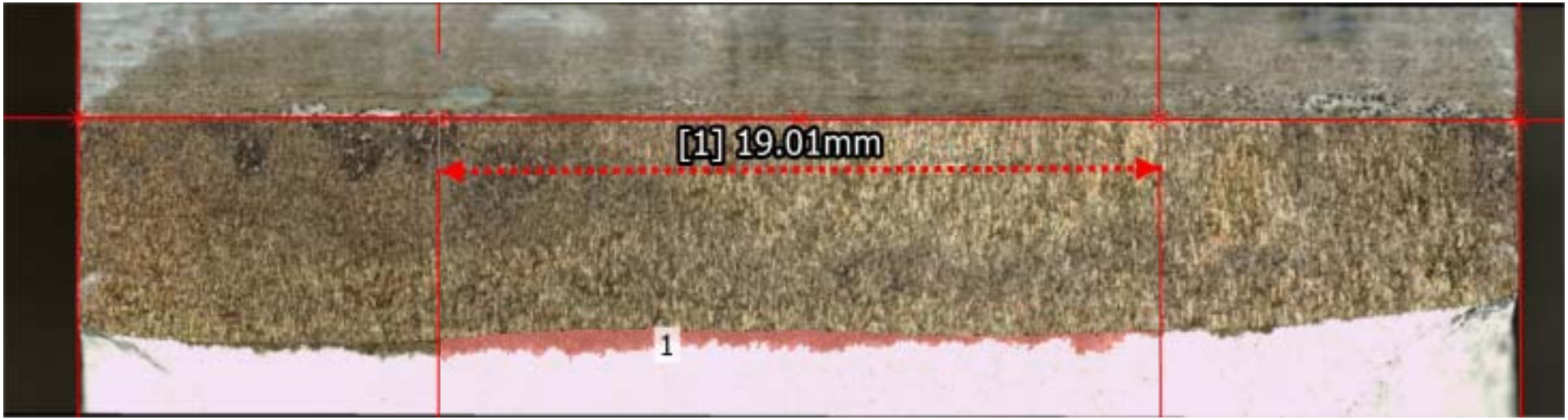
K_{Isi} Method

W = 76.2 mm
B = 38.1 mm
B_n = 38.1 mm
a = 38.8 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	50.227	47.5	---	2.65	Valid
K_{Isi}	49.649	46.9	---	2.72	Not Valid

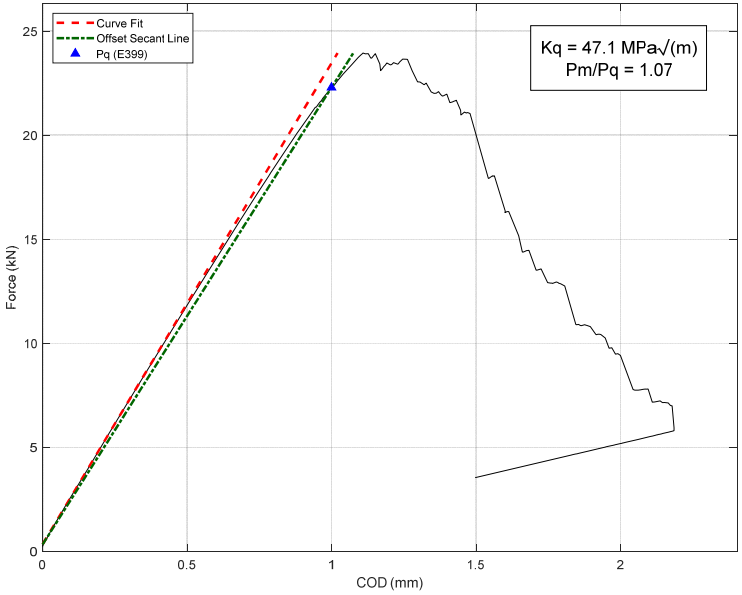
K-3-2-7 – Fracture Surface

Average extension: 0.38 mm

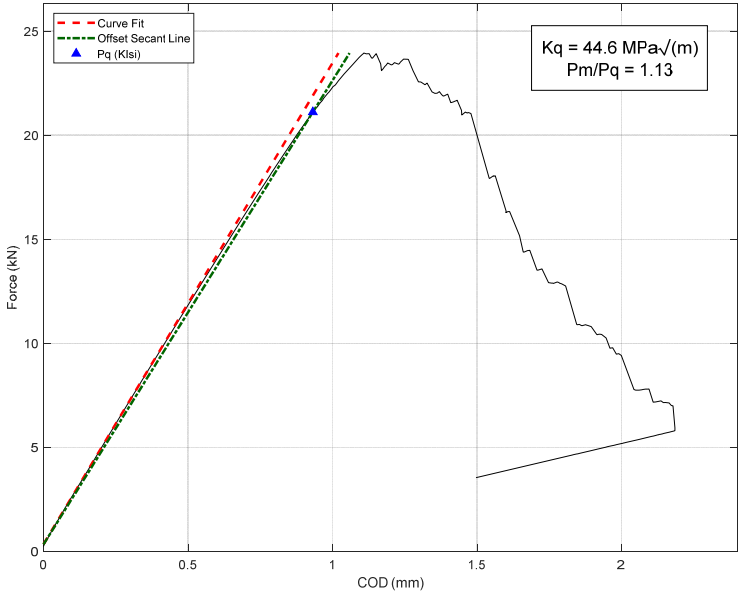


Area: 7.32 mm²

K-3-4-2 - E399 Test (Side Grooved)



K_{Ic} Method

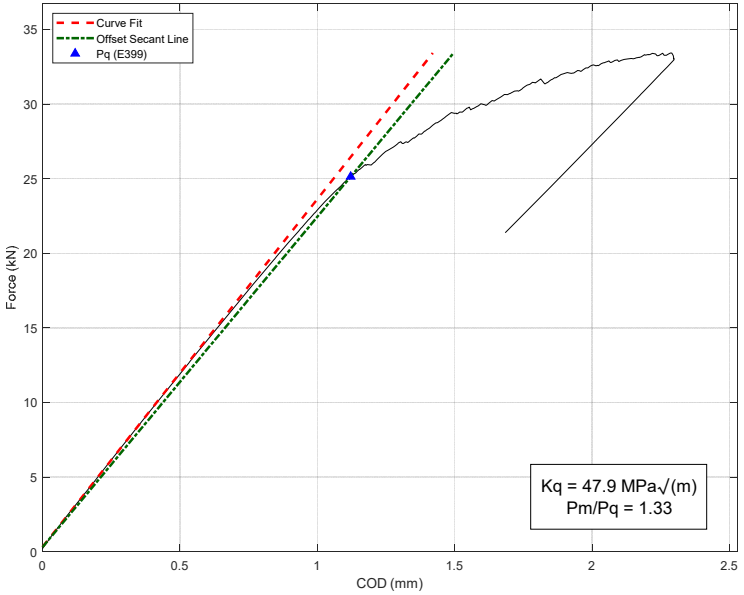


K_{Isi} Method

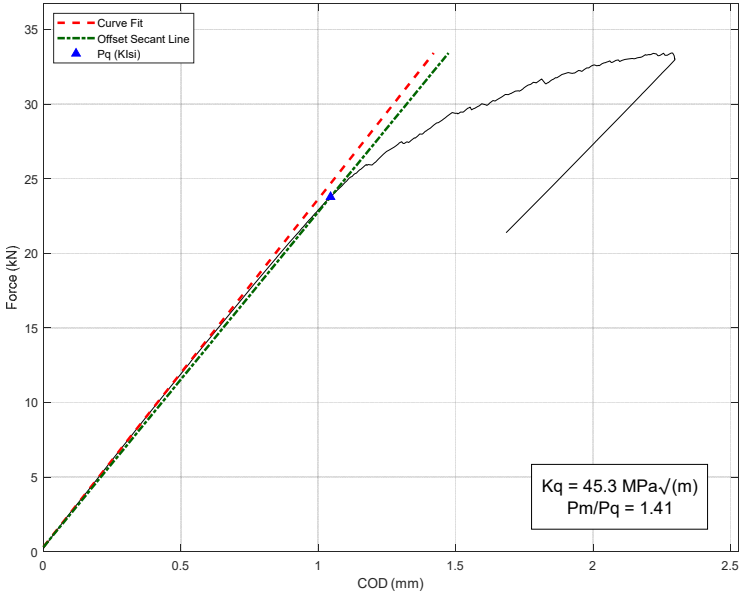
W = 76.2 mm
B = 18.9 mm
B_n = 15.2 mm
a = 38.7 mm
$M_{K,limit}$ (K_{Isi}) = 3.00

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	22.294	47.1	1.07	2.70	Valid
K_{Isi}	21.116	44.6	1.13	3.01	Valid

K-3-4-9 - E399 Test



K_{Ic} Method

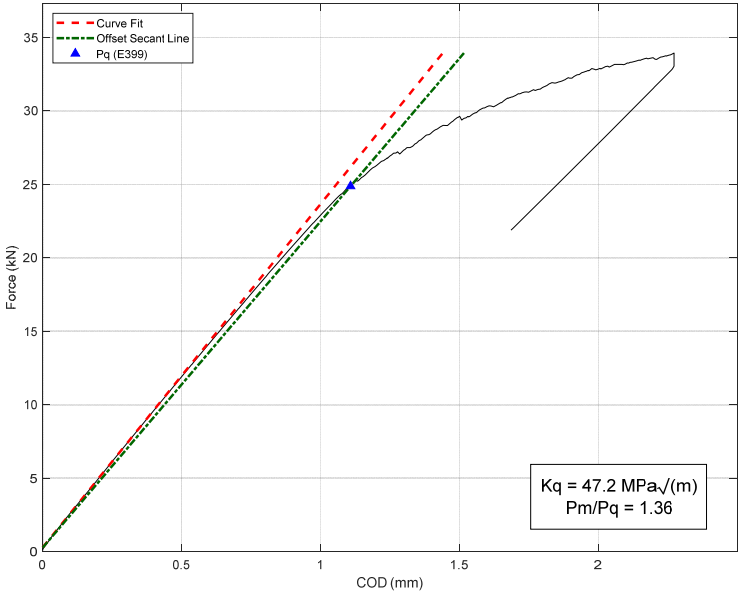


K_{Isi} Method

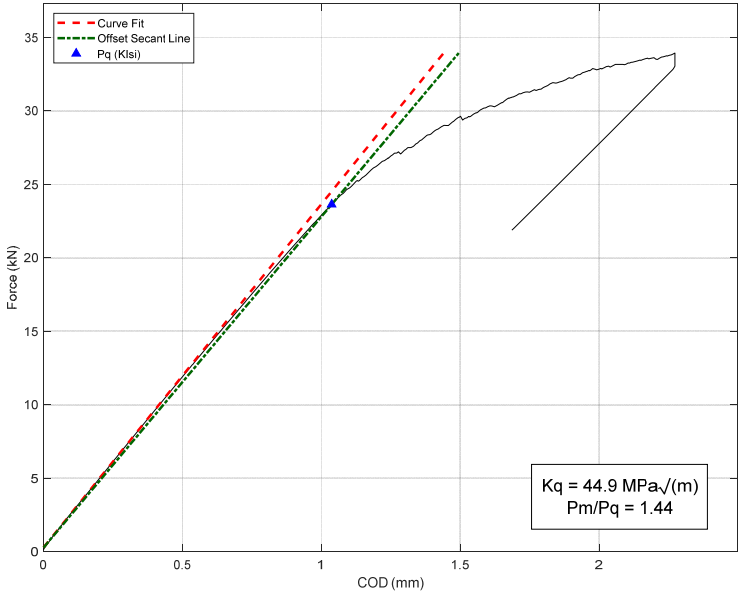
W = 76.2 mm
B = 19.0 mm
B_n = 19.0 mm
a = 38.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	25.138	47.9	1.33	2.60	Pm/Pq
K_{Isi}	23.780	45.3	1.41	2.91	Ligament

K-3-4-10 - E399 Test



K_{Ic} Method

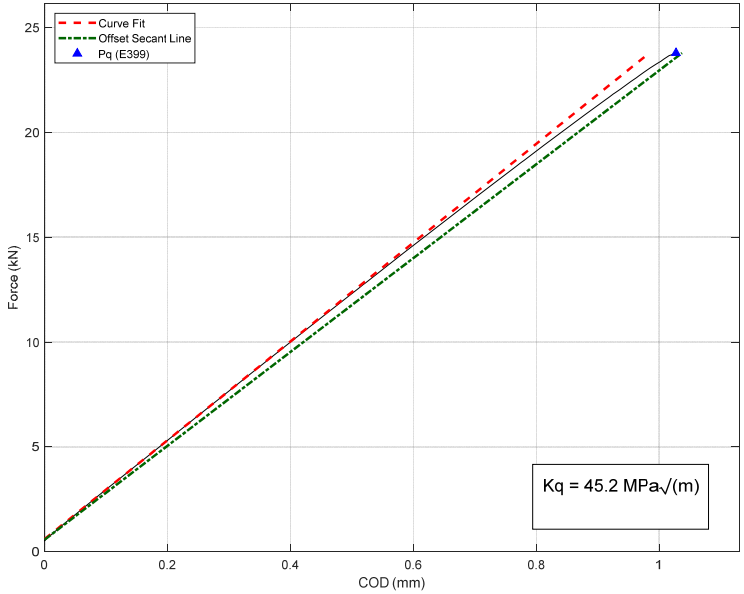


K_{Isi} Method

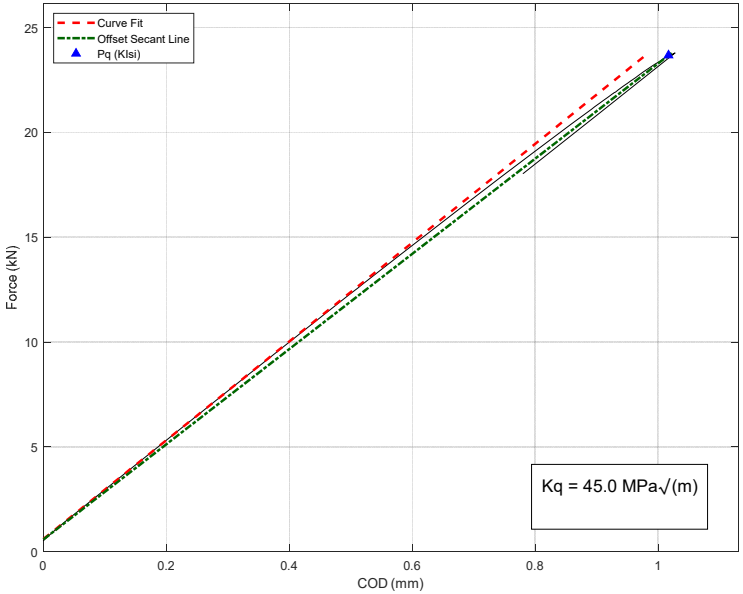
W = 76.2 mm
B = 19.0 mm
B_n = 19.0 mm
a = 38.8 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Validity
K_{Ic}	24.873	47.2	1.36	2.68	Pm/Pq
K_{Isi}	23.635	44.9	1.44	2.97	Ligament

K-3-4-5 - Interrupted Test



K_{Ic} Method

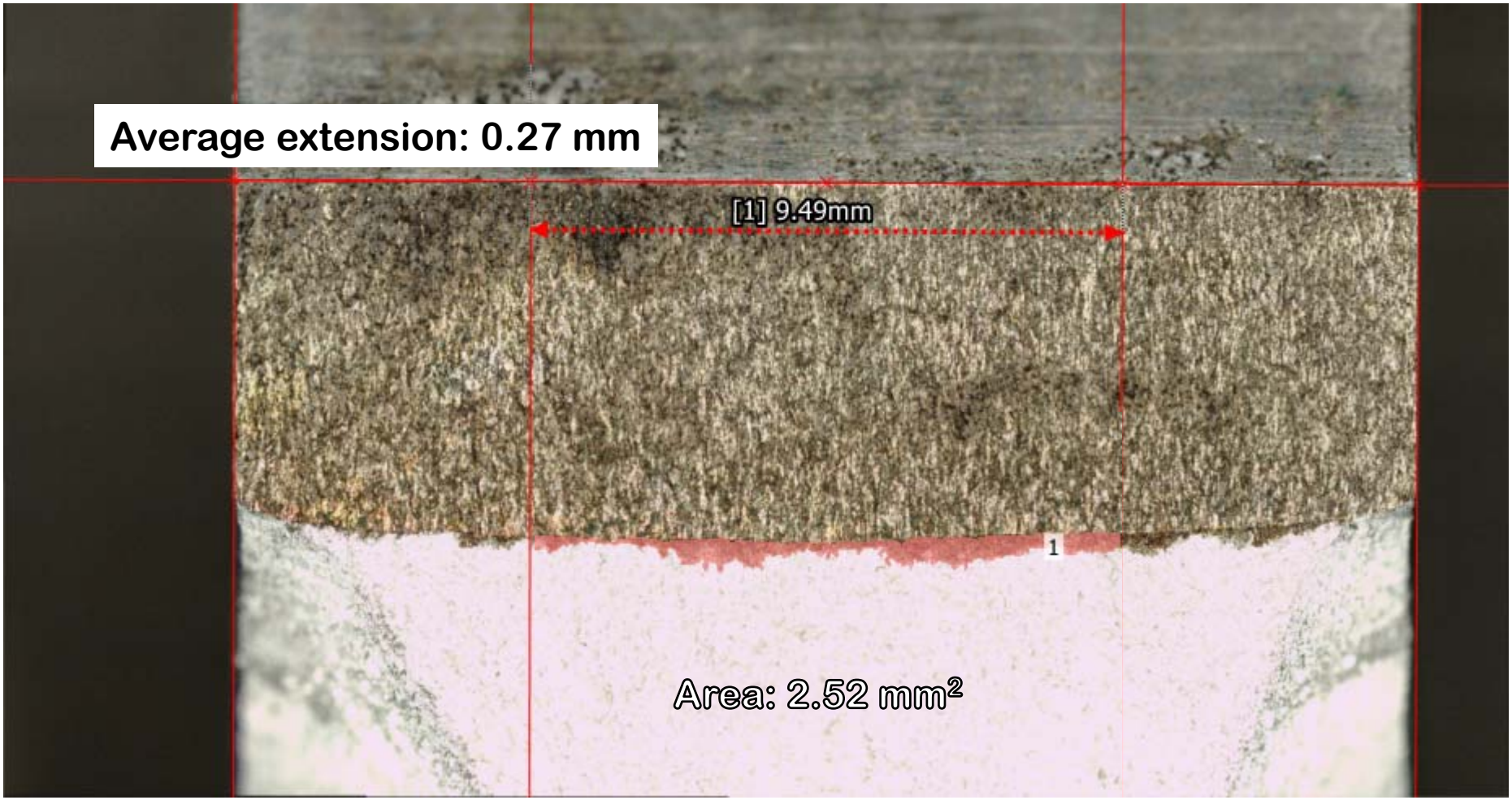


K_{Isi} Method

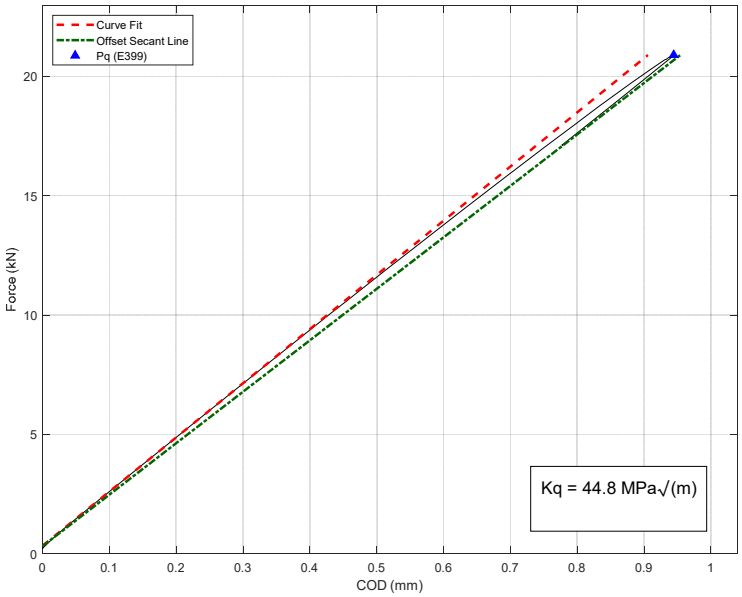
W = 76.2 mm
B = 19.0 mm
B_n = 19.0 mm
a = 38.8 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	23.783	45.2	---	2.92	Valid
K_{Isi}	23.671	45.0	---	2.95	Not Valid

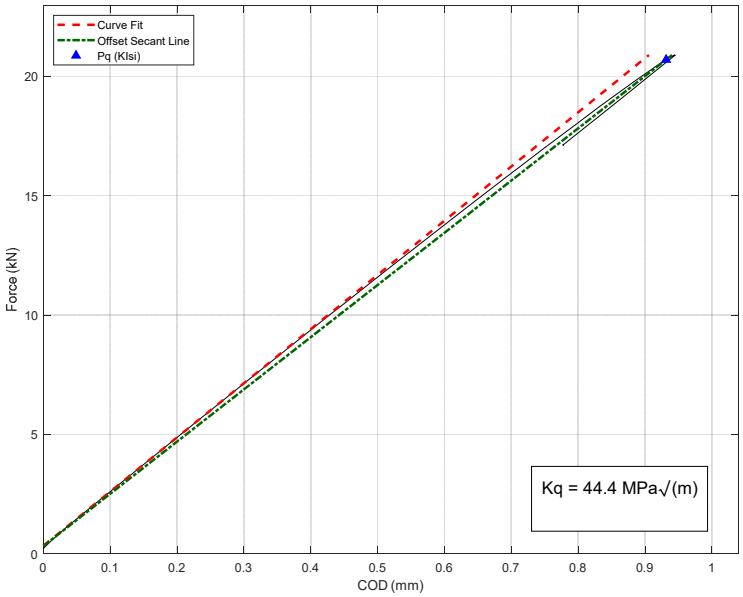
K-3-4-5 – Fracture Surface



K-3-4-6 - Interrupted Test



K_{Ic} Method

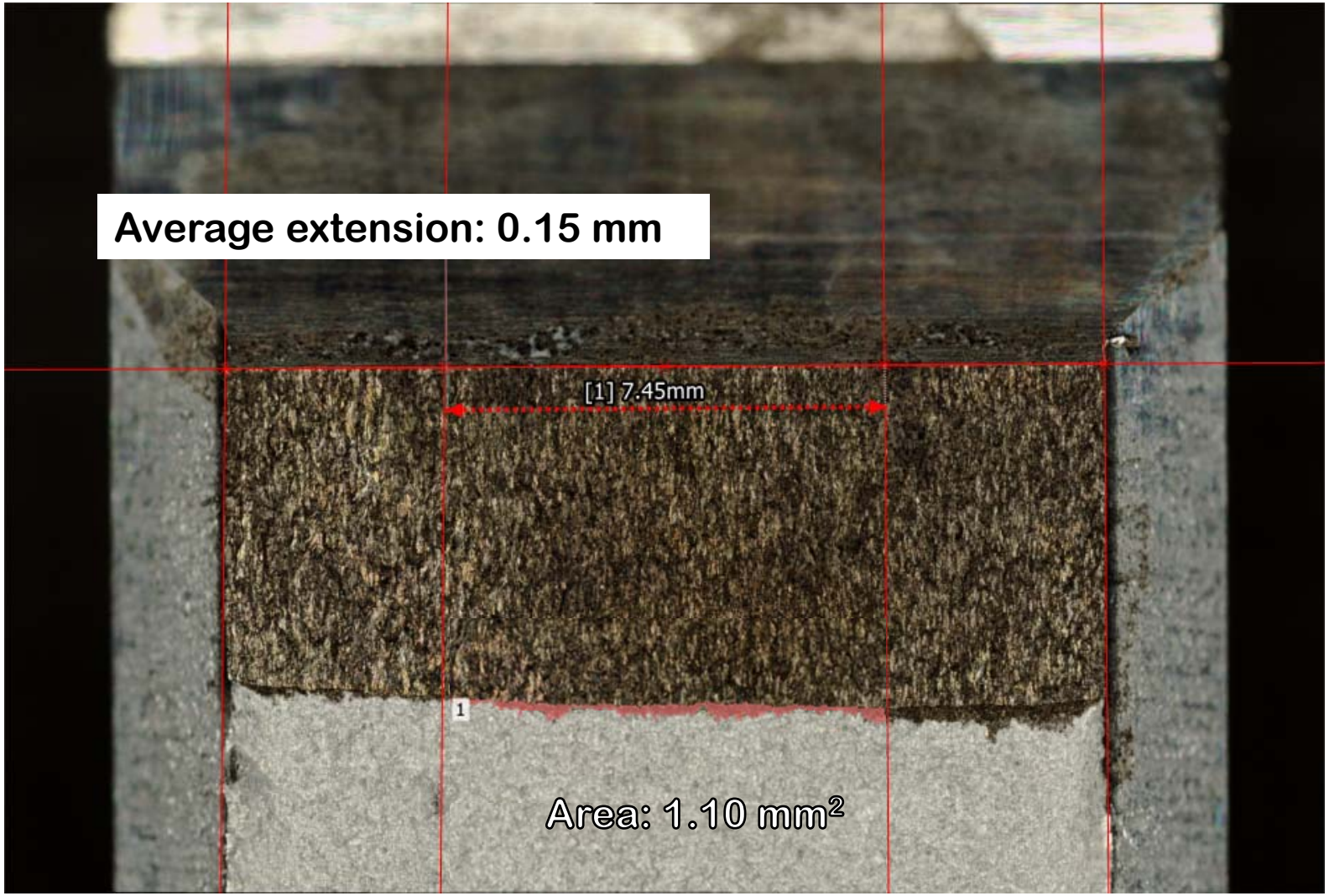


K_{Isi} Method

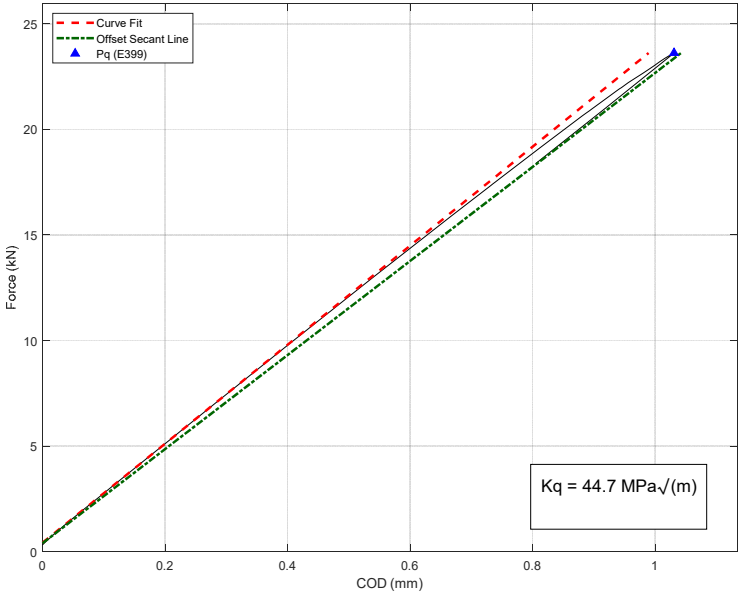
W = 76.2 mm
B = 19.0 mm
B_n = 15.0 mm
a = 38.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.98

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	20.897	44.8	---	2.96	Valid
K_{Isi}	20.701	44.4	---	3.02	Valid

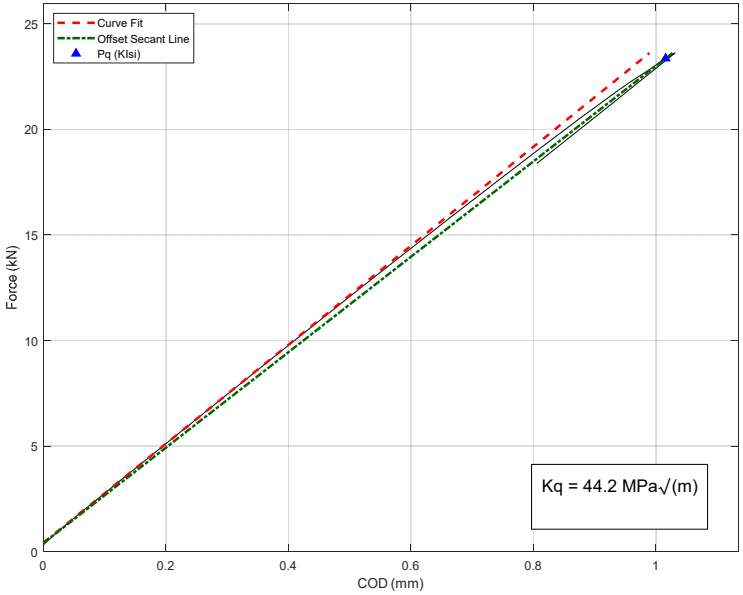
K-3-4-6 – Fracture Surface



K-3-4-8 - Interrupted Test



K_{Ic} Method



K_{Isi} Method

W = 76.2 mm
B = 19.0 mm
B_n = 19.0 mm
a = 38.8 mm
$M_{K,limit}$ (K_{Isi}) = 2.99

	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	23.615	44.7	---	3.00	Valid
K_{Isi}	23.359	44.2	---	3.06	Valid

K-3-4-8 – Fracture Surface