ASTM E399 Standard Development – K_{Isi} Analysis Method

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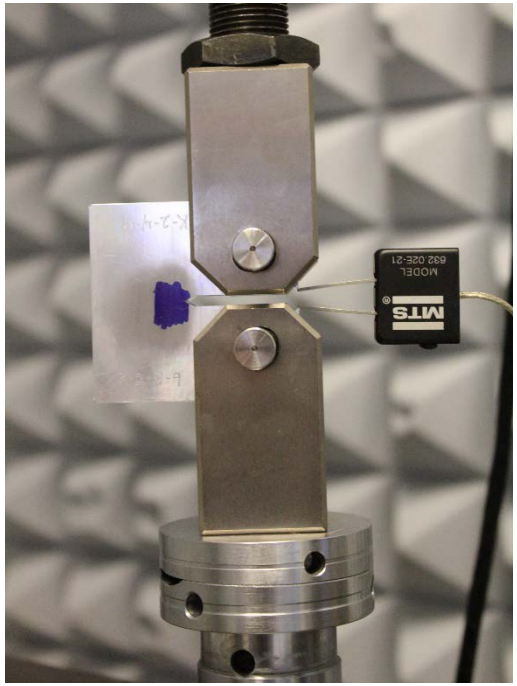
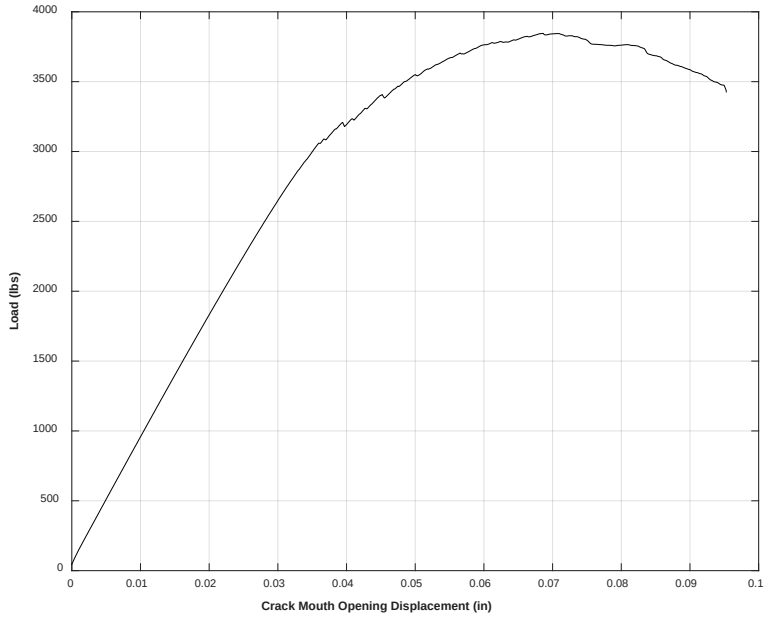
Background

- 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 pre-cracked test specimen to failure while recording the applied load and the crack mouth opening displacement.



Example Test Setup



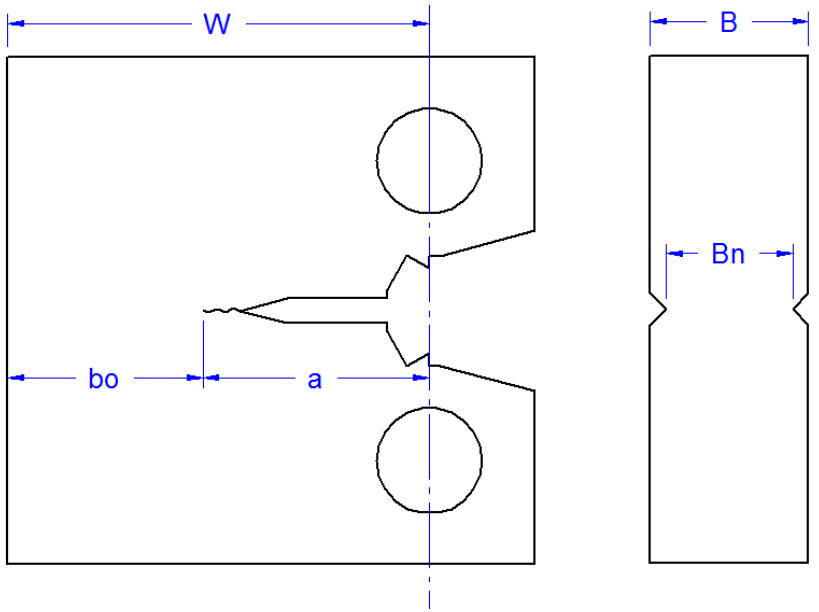
Example Test Record

Background

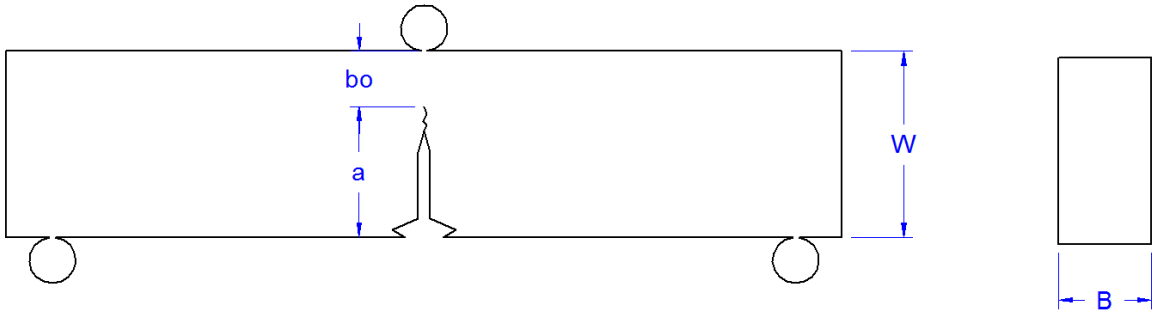
- Several test specimen types are allowable per ASTM E399; two common geometries are the compact tension (C(T)) and the single-edge bend (SE(B)) geometries.

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

Compact Tension (C(T))

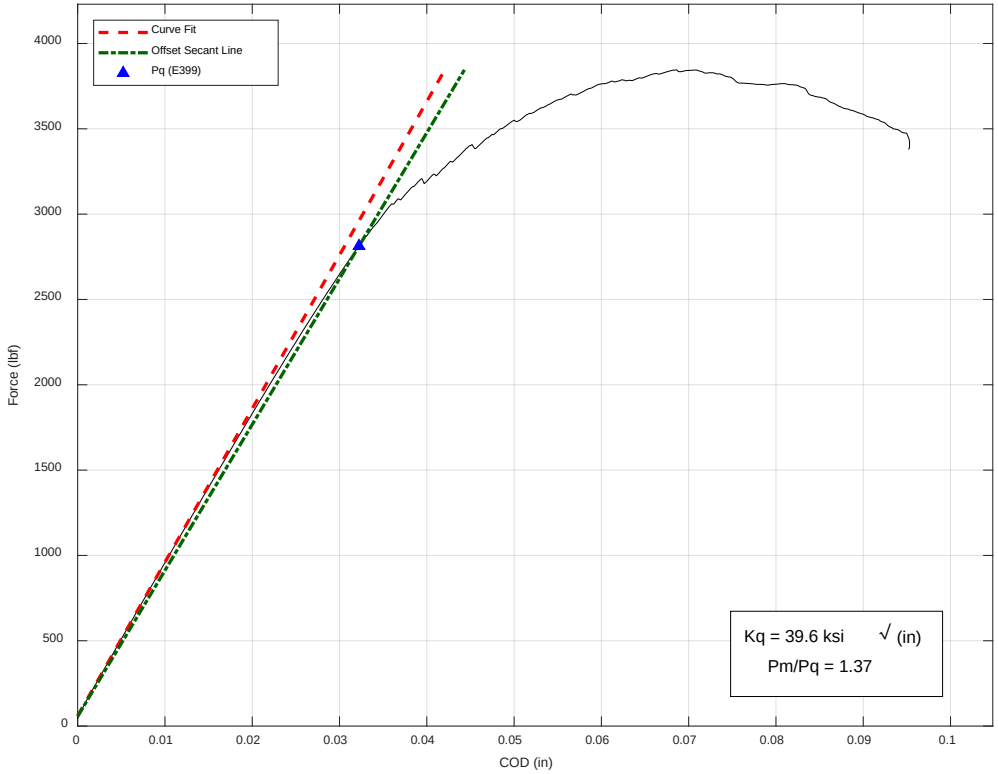


Single Edge Bend (SE(B))



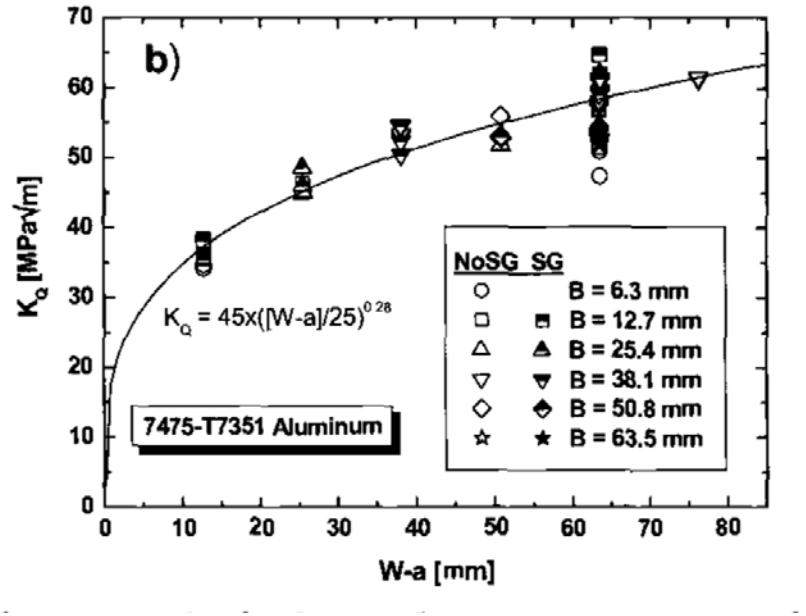
Background

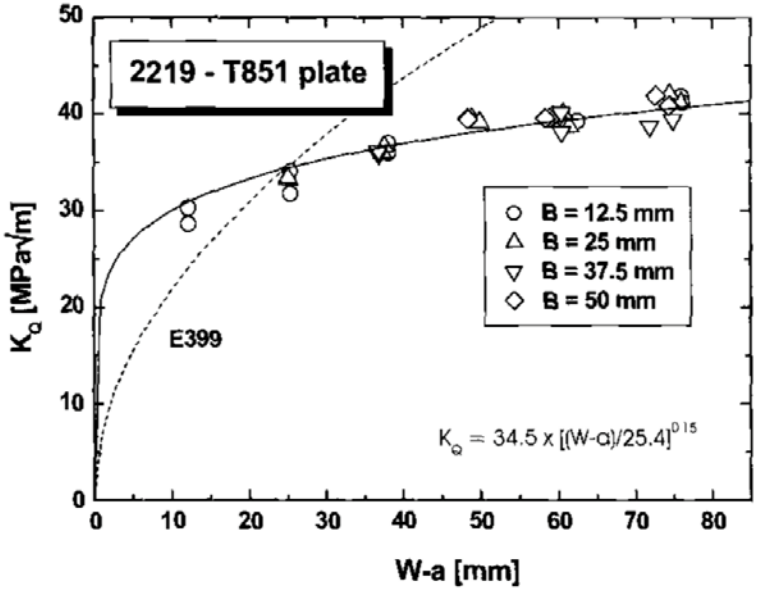
- The test result is an estimate of the plane-strain fracture toughness, K_q, determined by the intercept of the test record with a 95% secant-offset construction line.
- The 95% offset represents crack extension corresponding to ~2% of the original specimen ligament (assuming that all compliance change 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

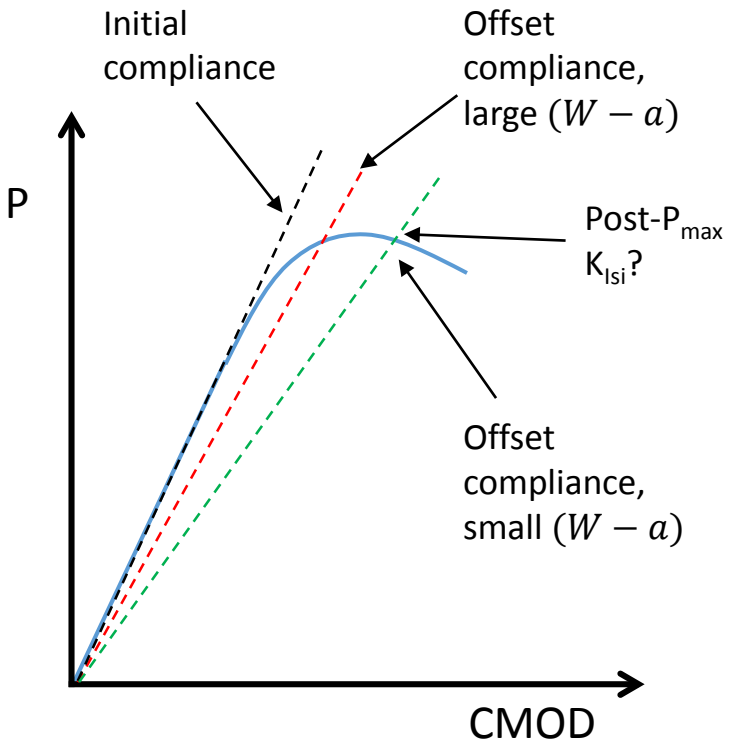
K_{Isi} Analysis Method

- 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).

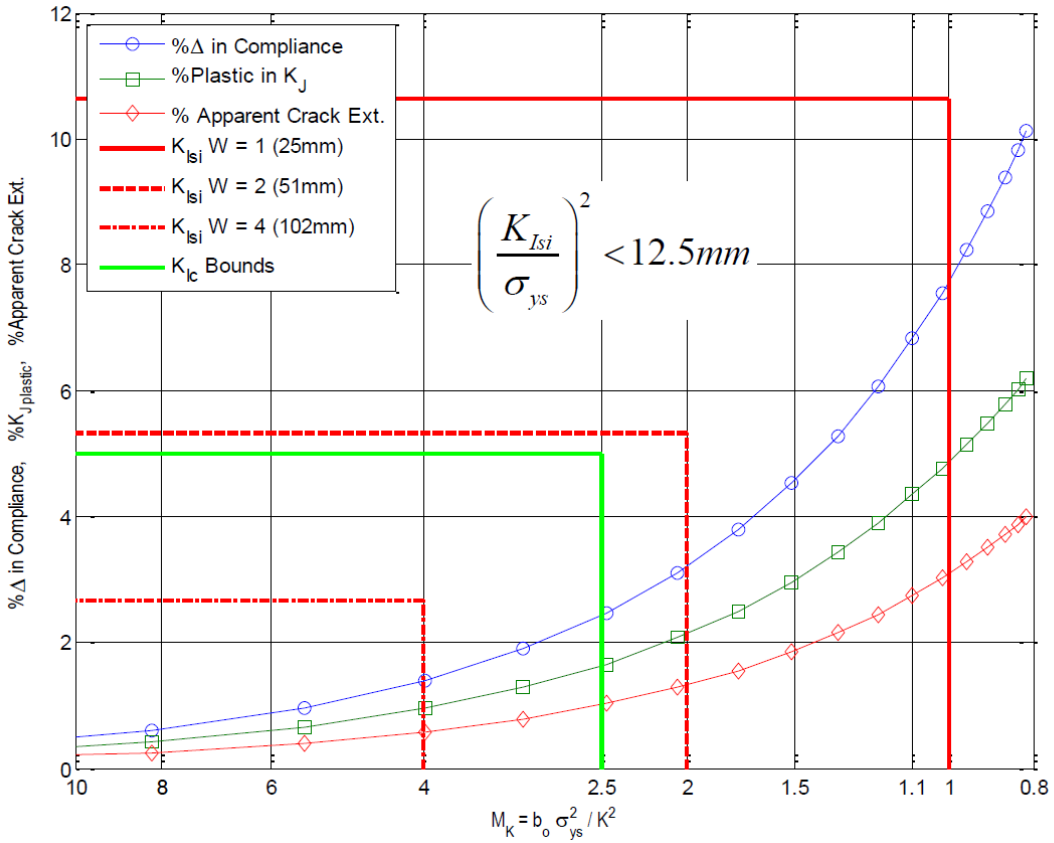
$$\left(\frac{K_{Isi}}{\sigma_{YS}}\right)^2 < 12.5$$



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

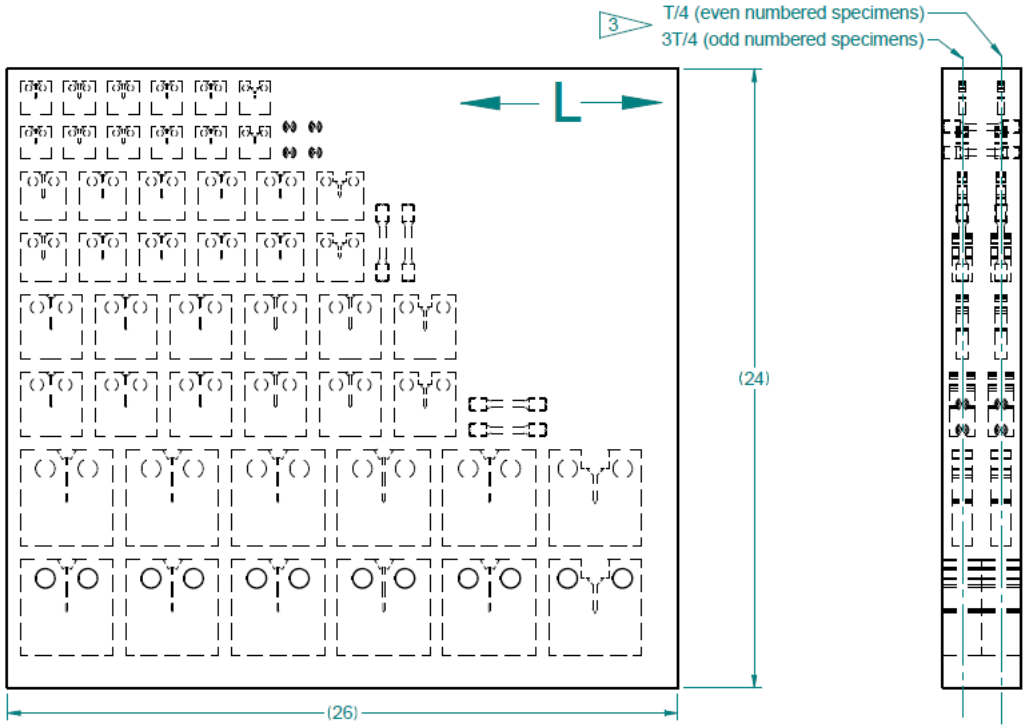
M. James, D. Wells, P. Allen and K. Wallin, "A Review of the Proposed KIsi Offset-Secant Method for Size-Insensitive Linear Elastic Fracture Toughness Evaluation," *17th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics*, 2017.

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

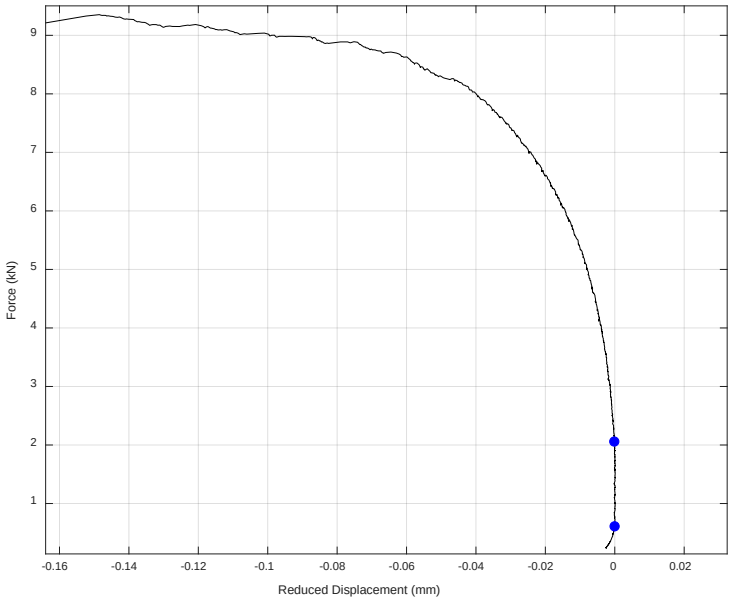
- All specimens have L-T orientation.
- Several spares for each specimen configuration are available for additional testing.

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

Completed

Slope Fitting

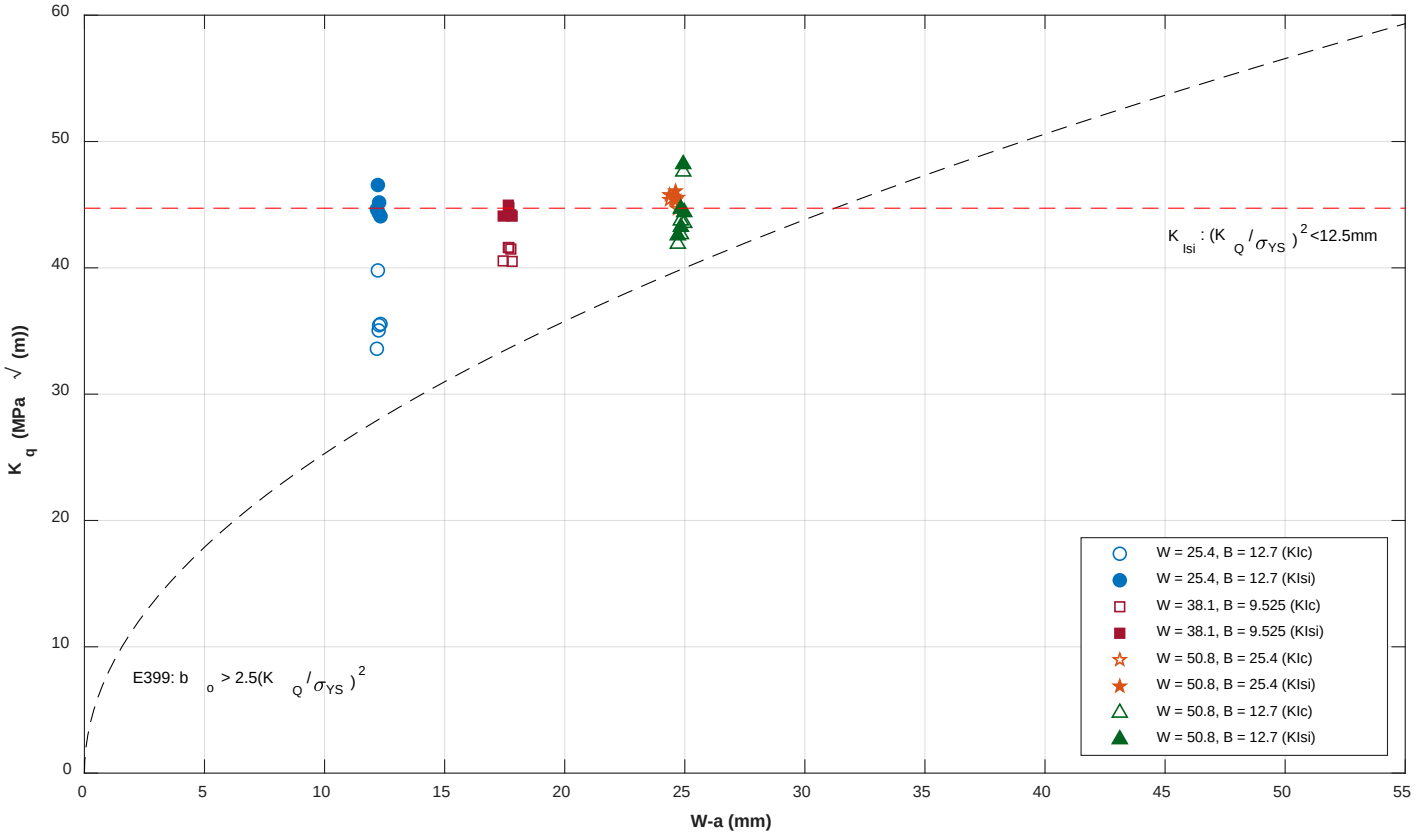
- Slope determination for the purposes of determining the K_{Ic} and K_{Isi} points is done by using the Slope Determination through Analysis of Residuals (SDAR) method, developed by Graham and Adler.
- The SDAR algorithm provides an objective and repeatable method for slope determination.
- The response 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.

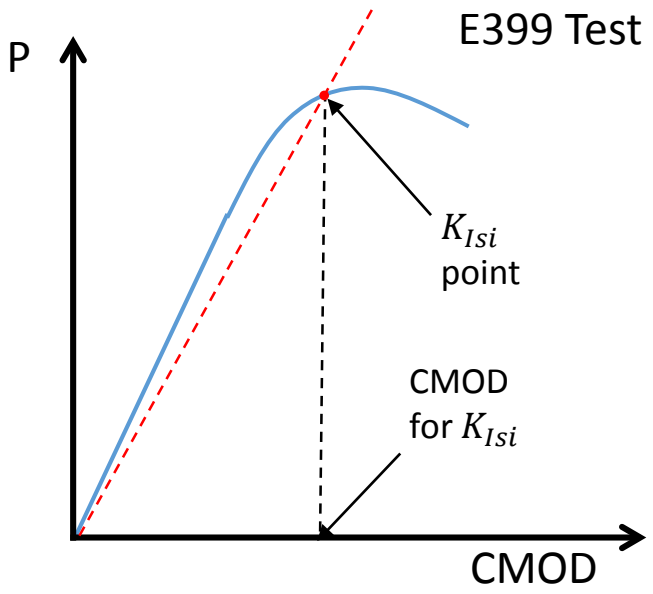
K Results

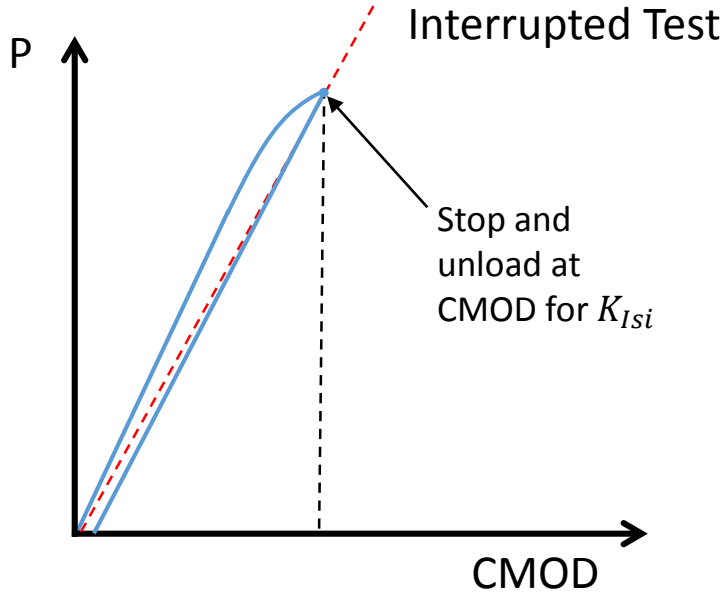
- Results obtained thus far from four specimen configurations.
- In general, the K_{Isi} results are more consistent than the E399 K_{Ic} results. Data shown includes results from interrupted tests, if applicable.



Interrupted Tests

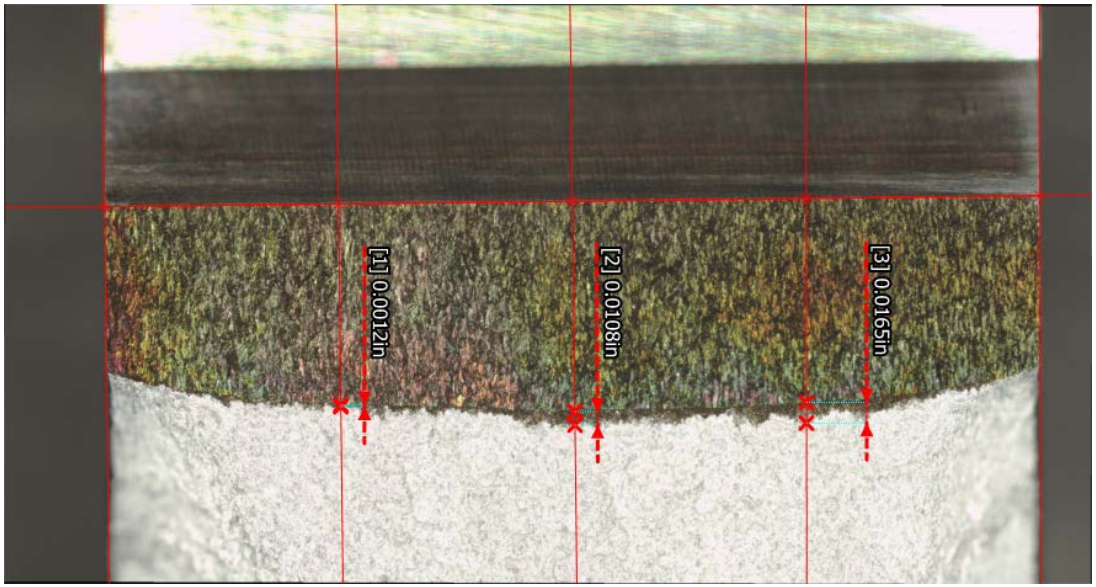
- Goal is to validate that the K_{Isi} point corresponds to 0.5 mm of crack extension.
- Samples will be precracked as close as possible to the lengths of the standard E399 tests using compliance crack monitoring techniques.
- E399 test will be conducted, but halted at the CMOD corresponding to the K_{Isi} point from the E399 tests.
- Specimens will be chemically stained 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.
- The current approach is to determine crack extension by the crack measurement method of E399; there has been limited crack extension at specimen edges, so only the middle three measurements are averaged.



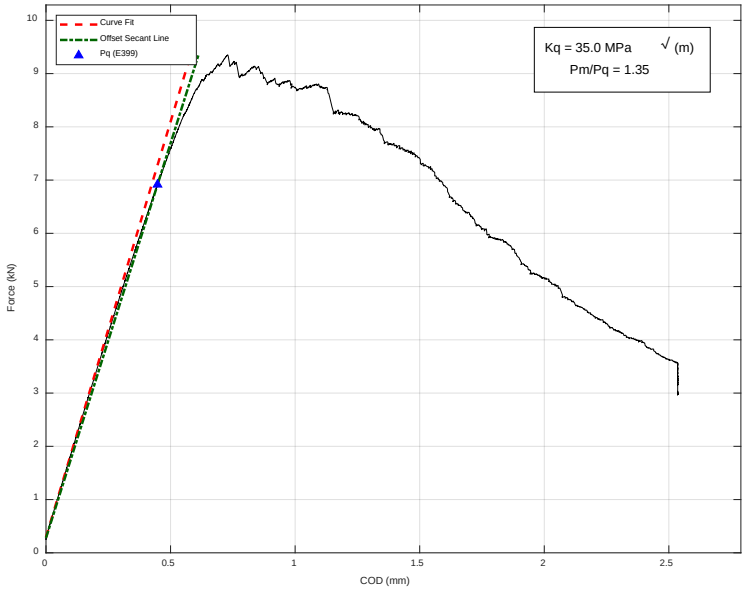
Interrupted Tests - Results

- In general, the K_{Isi} point has tended to underestimate the desired 0.5 mm of crack extension. 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.
- Future analysis will compare the measured crack extension with the predicted crack extension due to compliance change for the test.

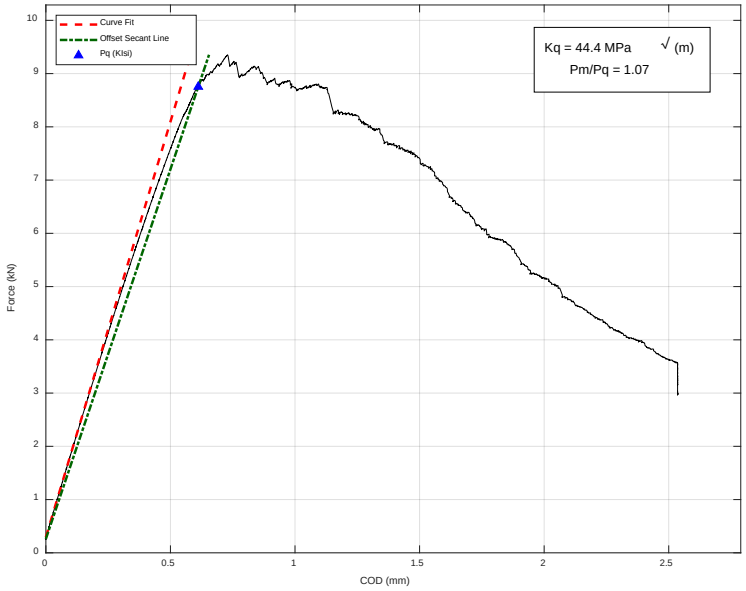
Specimen	W (mm)	B (mm)	$M_{K,limit}$	M_K @ K_{Isi}	K_{Isi}	Δa (mm)
K-1-2-1	25.4	12.7	0.98	0.96	45.2	0.23
K-1-2-4	25.4	12.7	0.99	1.01	44.1	0.15
K-15-2-2	38.1	19.0	1.42	1.45	44.2	0.35
K-15-2-8	38.1	19.0	1.41	1.41	44.8	0.24
K-2-2-1	50.8	25.4	1.96	1.88	45.6	0.41
K-2-2-8	50.9	25.4	1.98	1.90	45.6	0.41
K-2-4-6	50.8	12.6	1.98	2.18	42.6	0.50
K-2-4-8	50.8	12.6	1.99	2.12	43.2	0.28

Detailed Results

K-1-2-2 - E399 Test



K_{Ic} Method

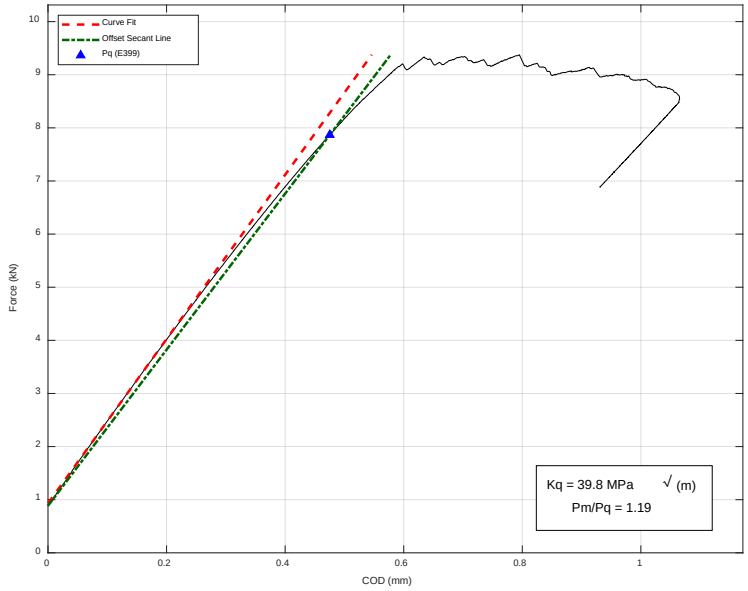


K_{Isi} Method

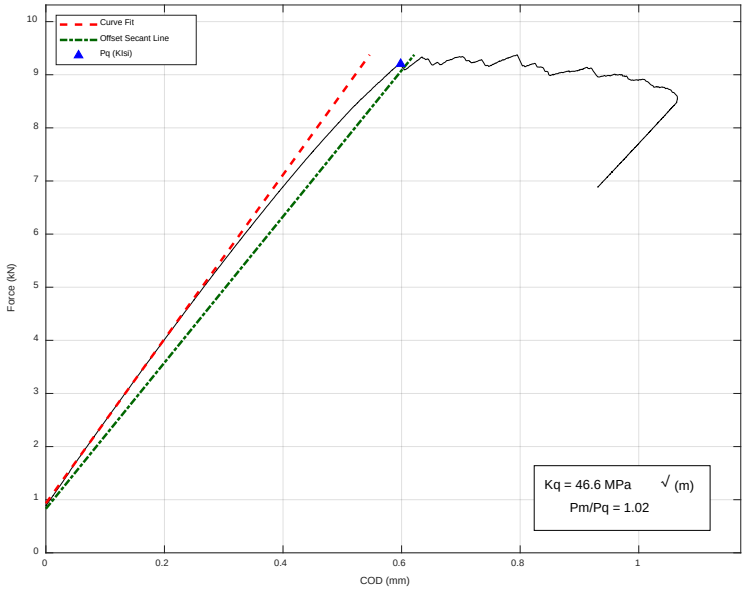
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.2 mm
$M_{K,limit}$ (K_{Isi}) = 0.98

	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-1-2-9 - E399 Test



K_{Ic} Method

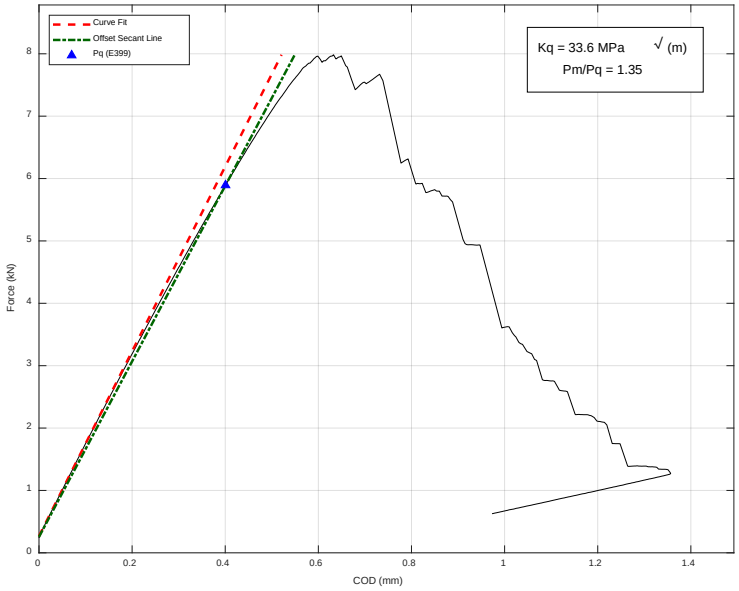


K_{Isi} Method

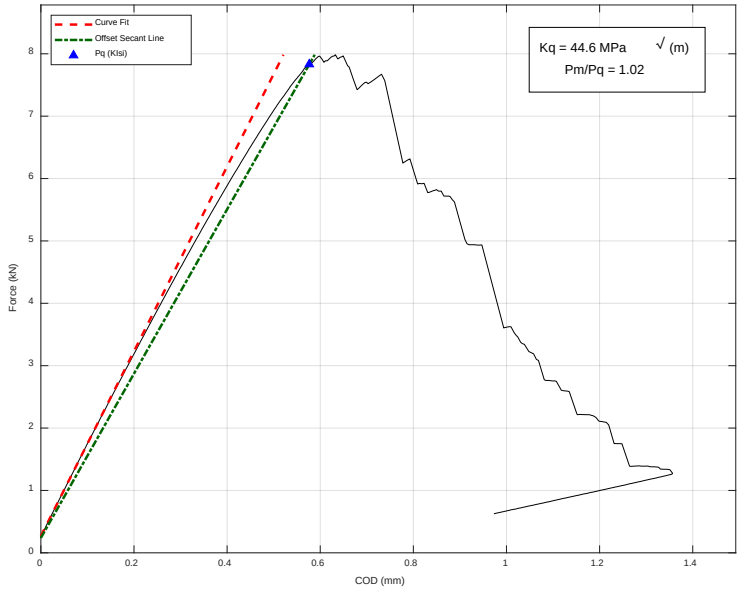
W = 25.4 mm
B = 12.7 mm
B_n = 12.7 mm
a = 13.2 mm
$M_{k,limit}$ (K_{Isi}) = 0.98

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



K_{Ic} Method

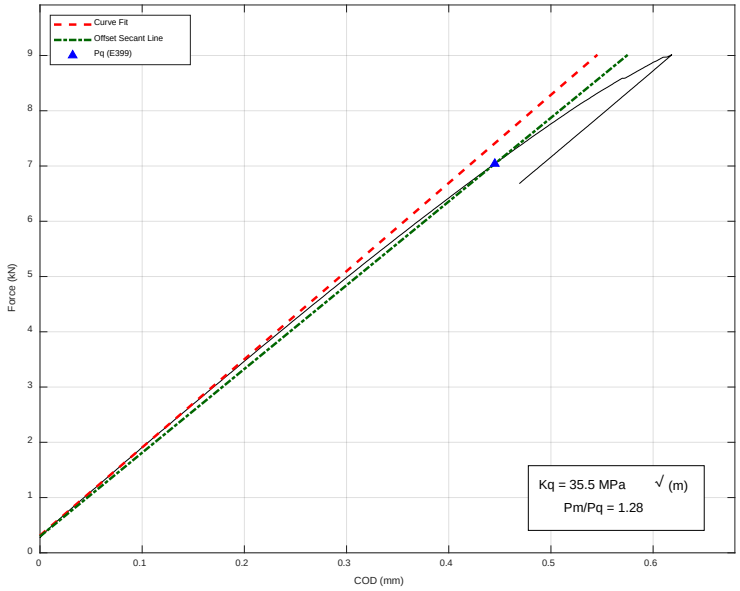


K_{Isi} Method

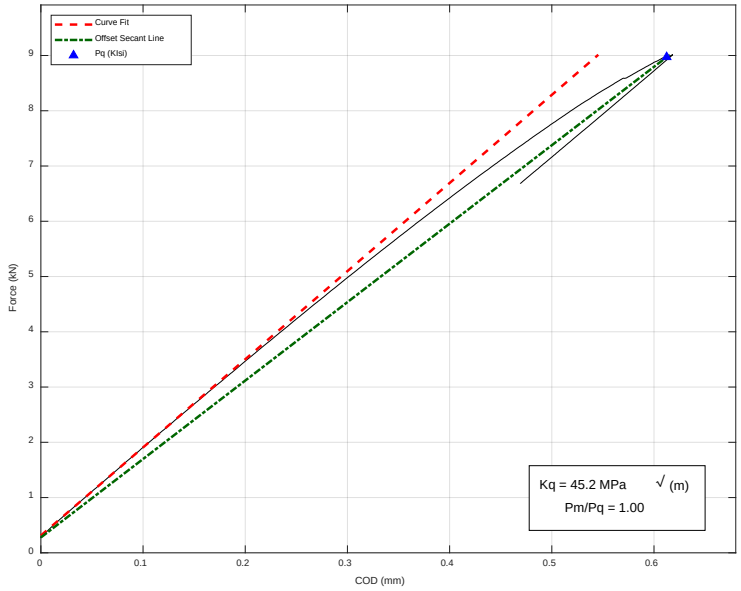
W = 25.4 mm
B = 12.7 mm
B_n = 10.2 mm
a = 13.3 mm
$M_{k,limit}$ (K_{Isi}) = 0.97

	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-1-2-1 - Interrupted Test



K_{Ic} Method

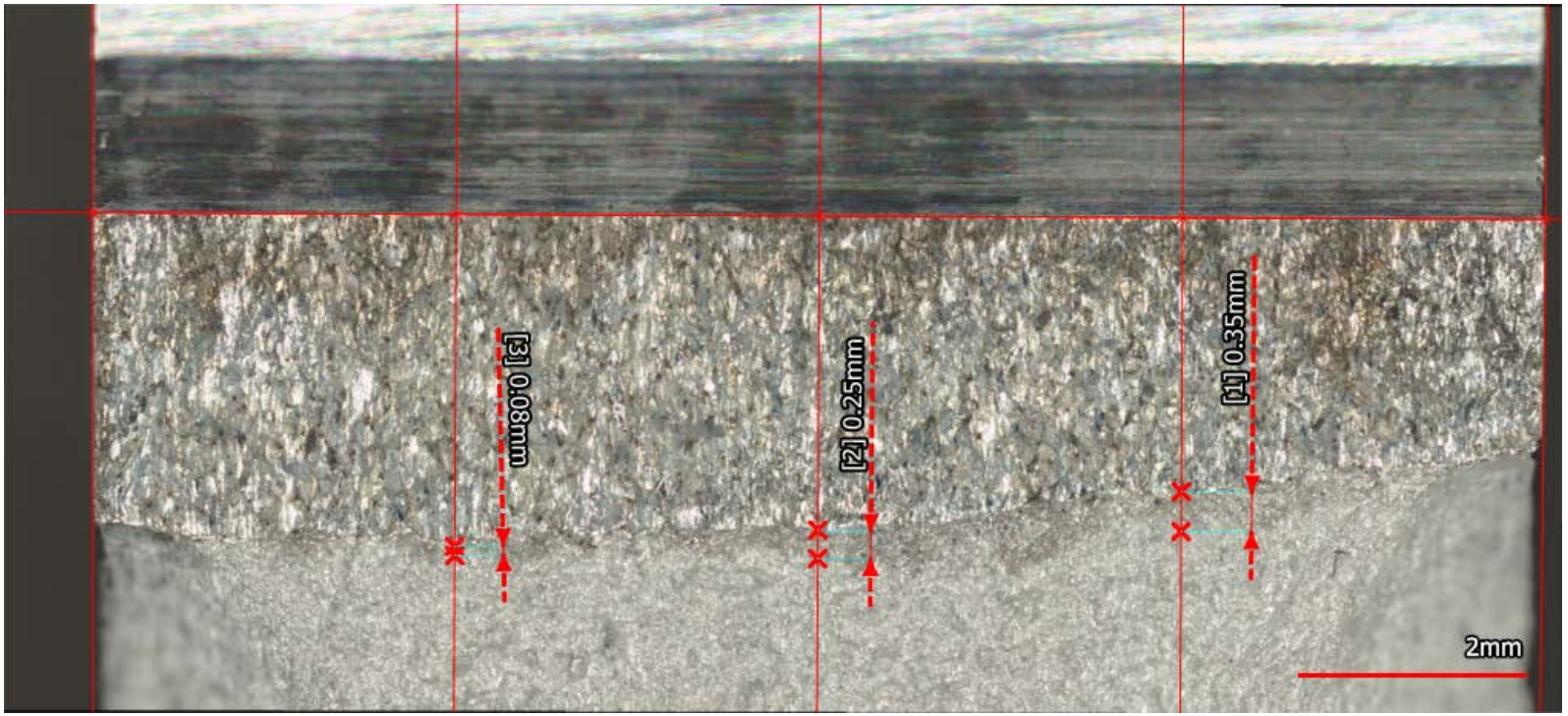


K_{Isi} Method

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

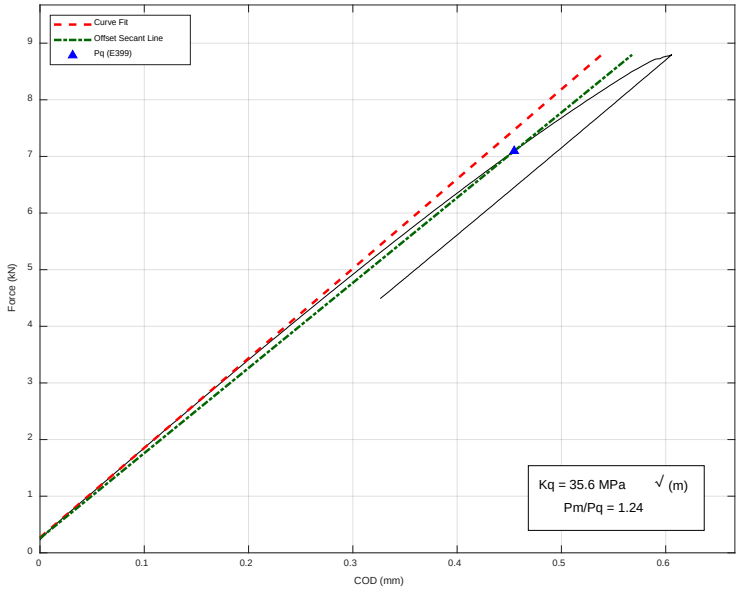
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	7.041	35.5	---	1.56	Not Valid
K_{Isi}	8.971	45.2	---	0.96	Not Valid

K-1-2-1 – Fracture Surface

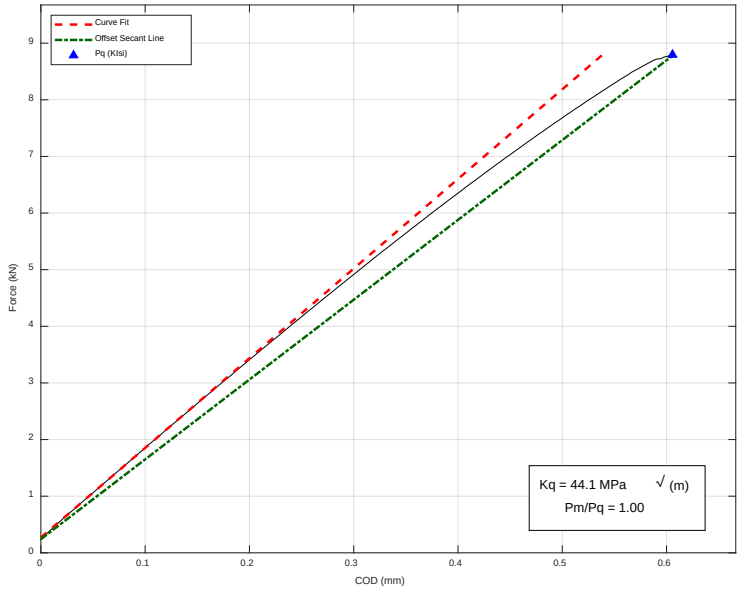


Average crack extension: 0.23 mm

K-1-2-4 - Interrupted Test



K_{Ic} Method

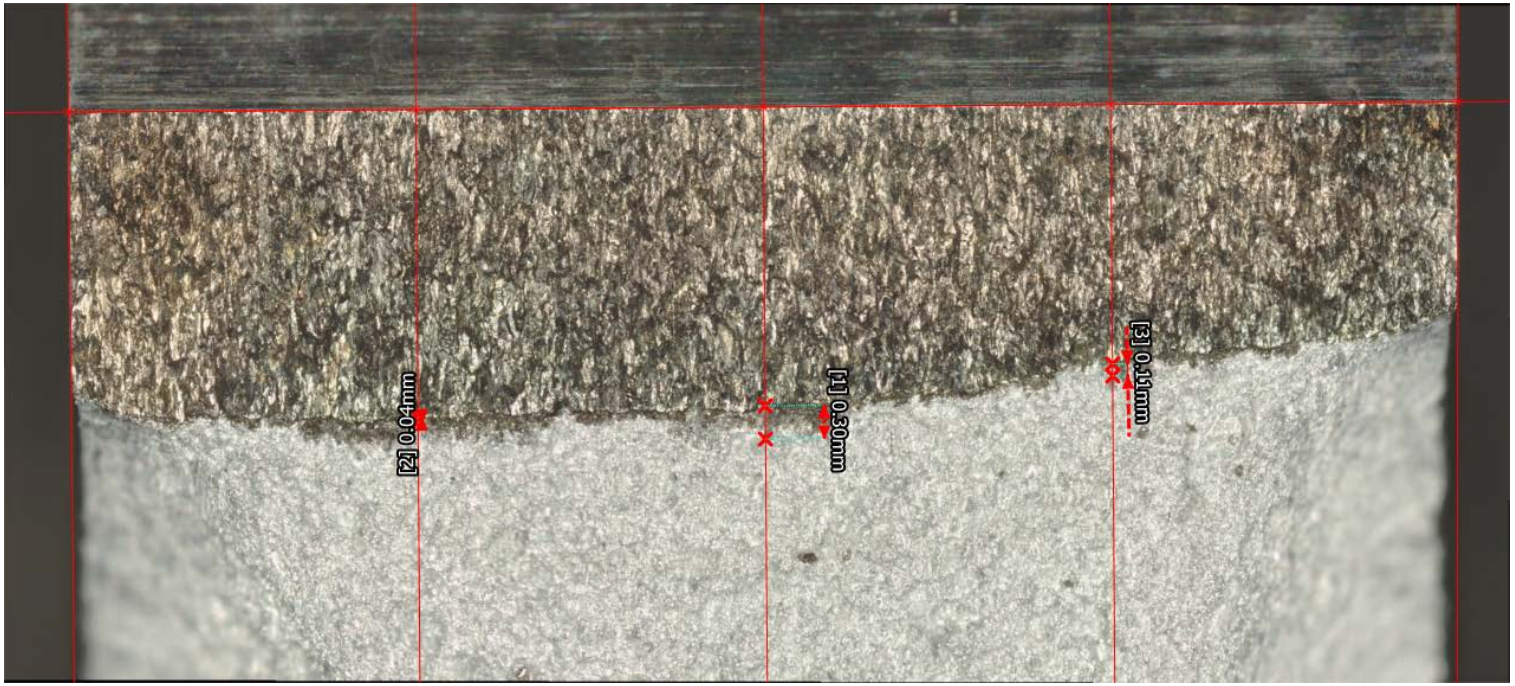


K_{Isi} Method

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

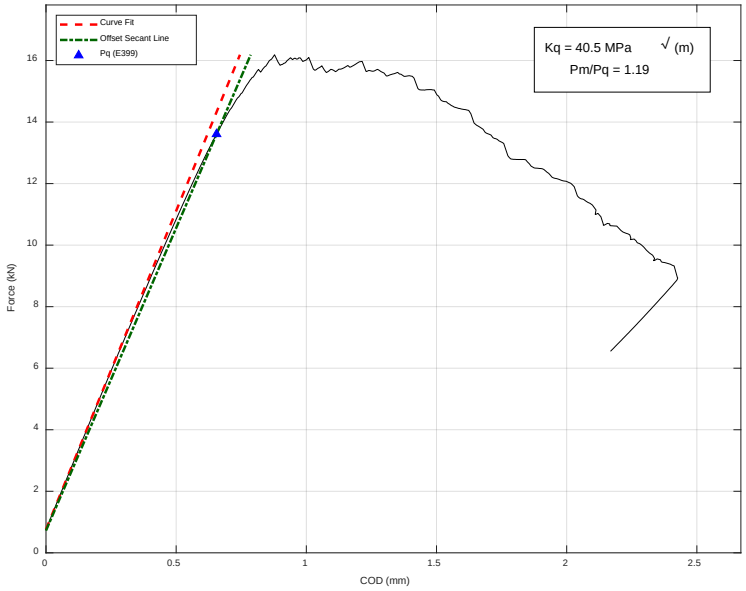
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	7.095	35.6	---	1.56	Not Valid
K_{Isi}	8.795	44.1	---	1.01	Valid

K-1-2-4 – Fracture Surface

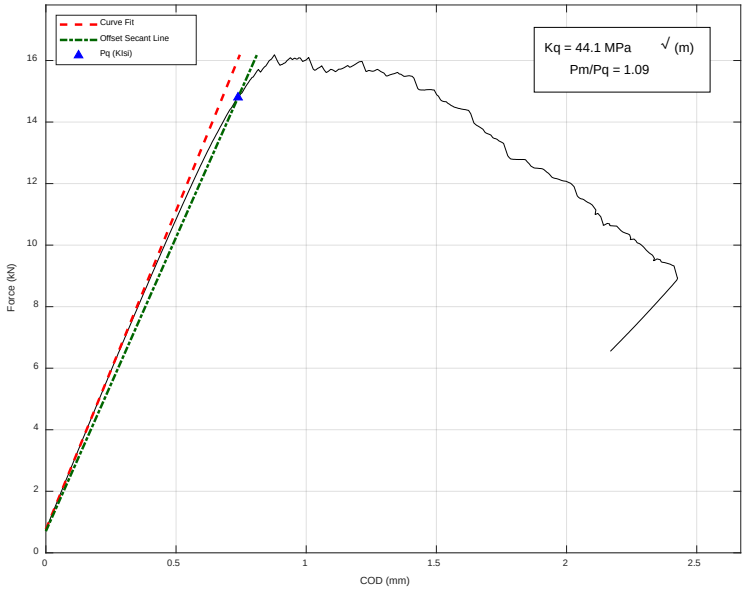


Average crack extension: 0.15 mm

K-15-2-5 - E399 Test



K_{Ic} Method

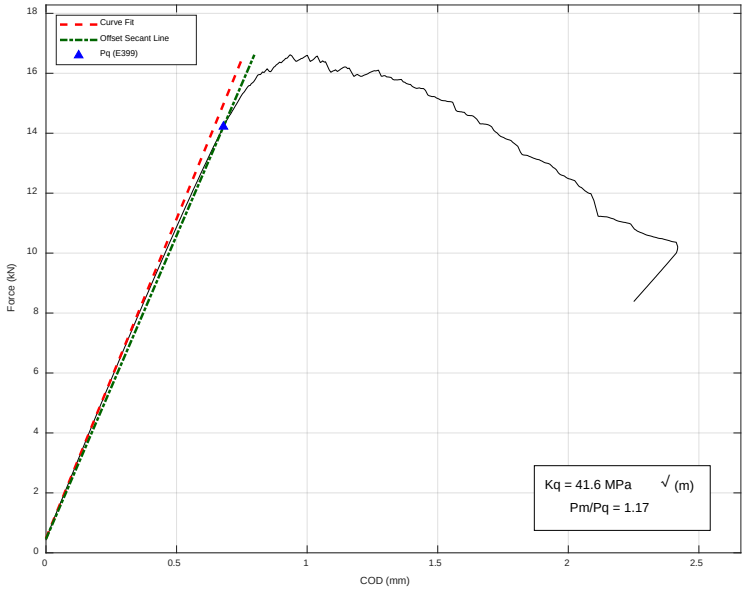


K_{Isi} Method

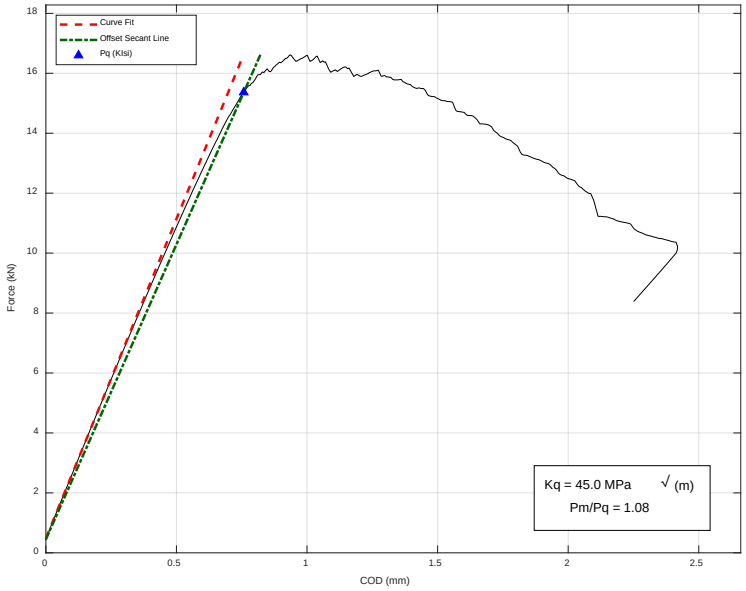
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.6 mm
$M_{k,limit}$ (K_{Isi}) = 1.39

	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

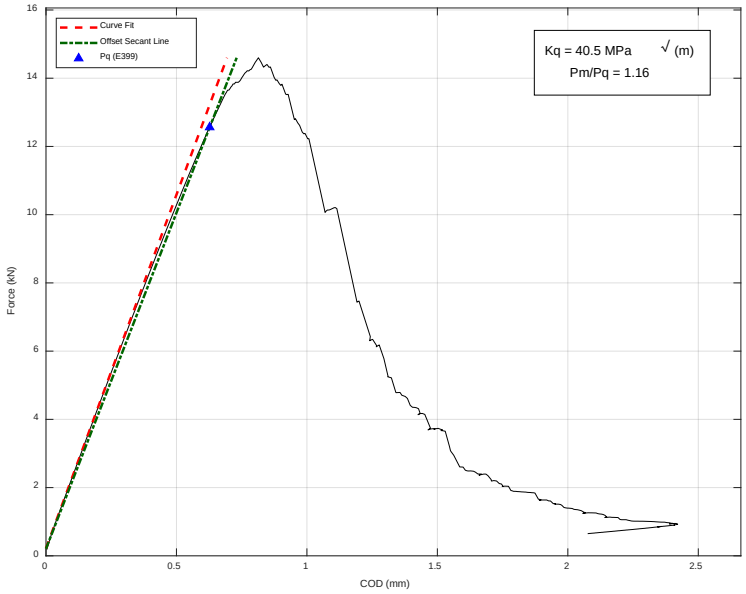


K_{Isi} Method

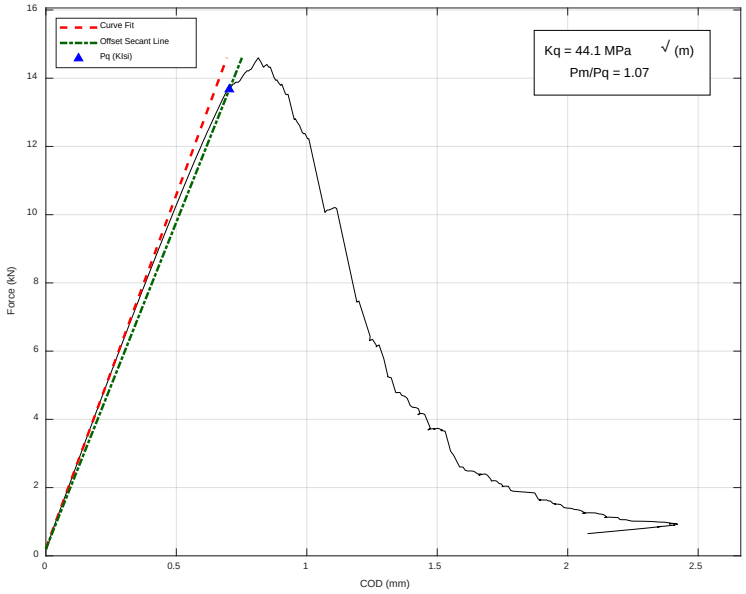
W = 38.1 mm
B = 19.0 mm
B_n = 19.0 mm
a = 20.4 mm
$M_{k,limit}$ (K_{Isi}) = 1.41

	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

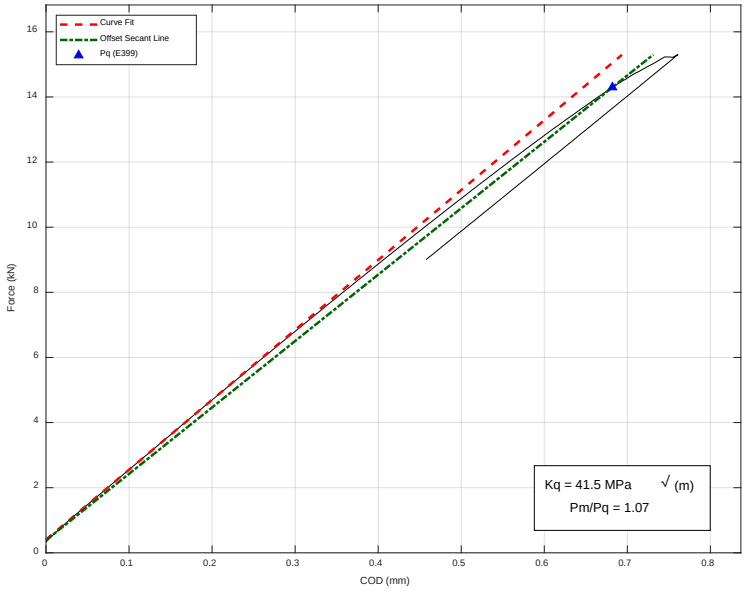


K_{Isi} Method

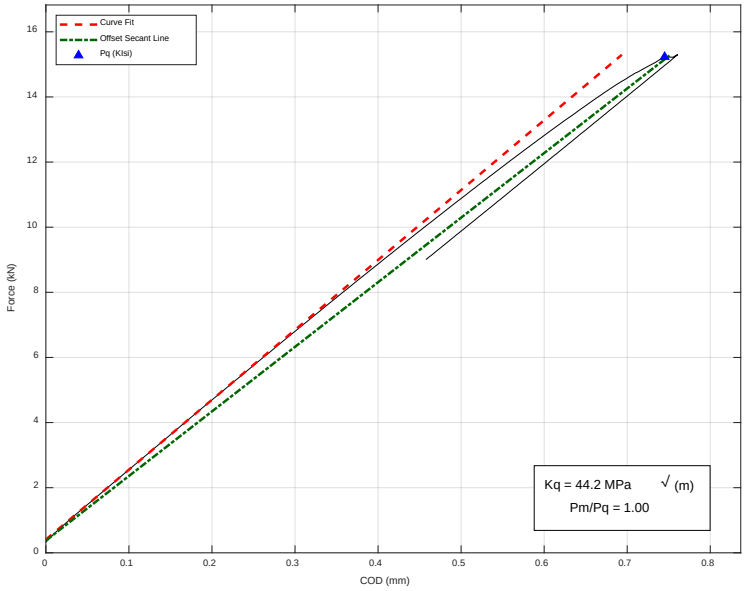
W = 38.1 mm
B = 19.0 mm
B_n = 15.3 mm
a = 20.3 mm
$M_{k,limit}$ (K_{Isi}) = 1.42

	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

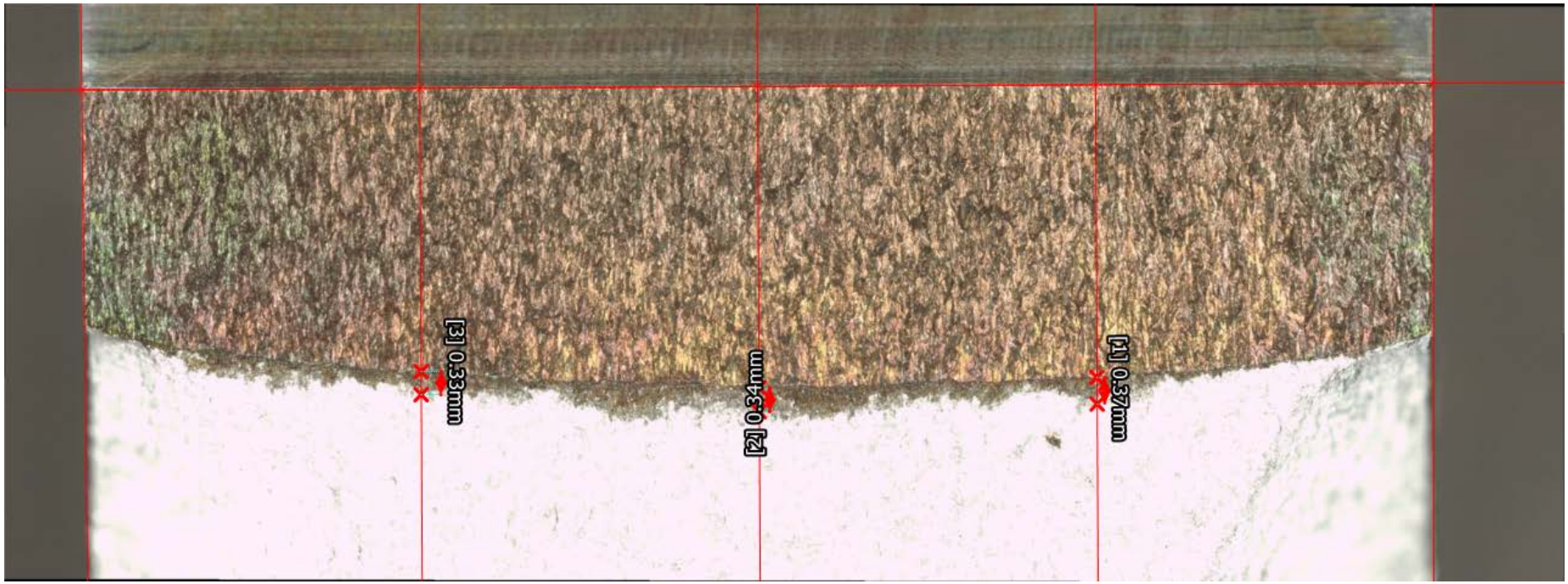


K_{Isi} Method

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

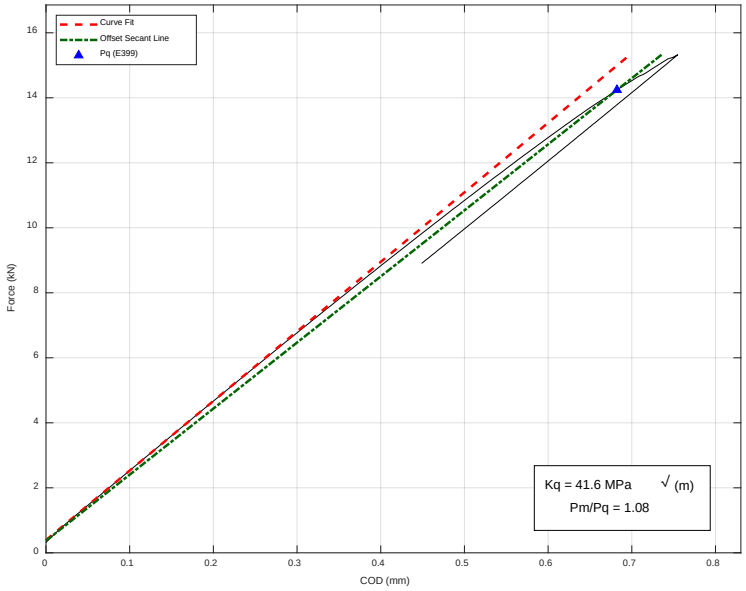
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	14.295	41.5	---	1.65	Not Valid
K_{Isi}	15.230	44.2	---	1.45	Valid

K-15-2-2 – Fracture Surface

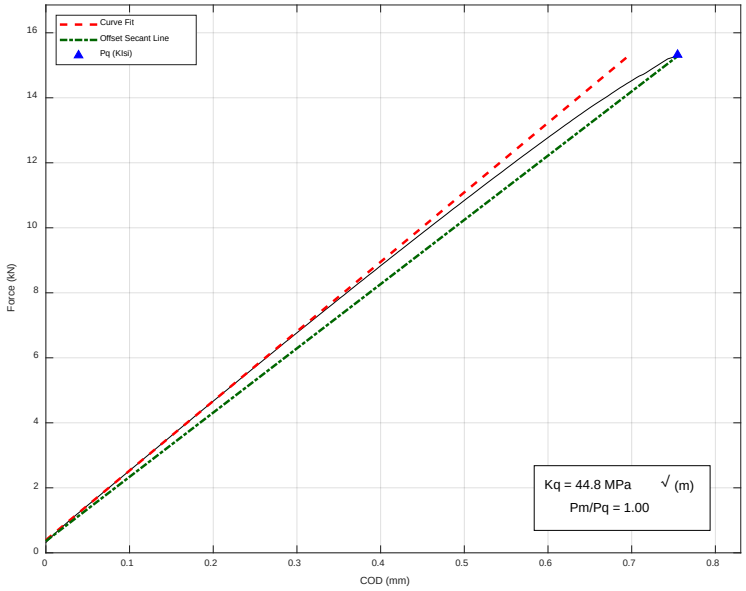


Average crack extension: 0.35 mm

K-15-2-8 - Interrupted Test



K_{Ic} Method

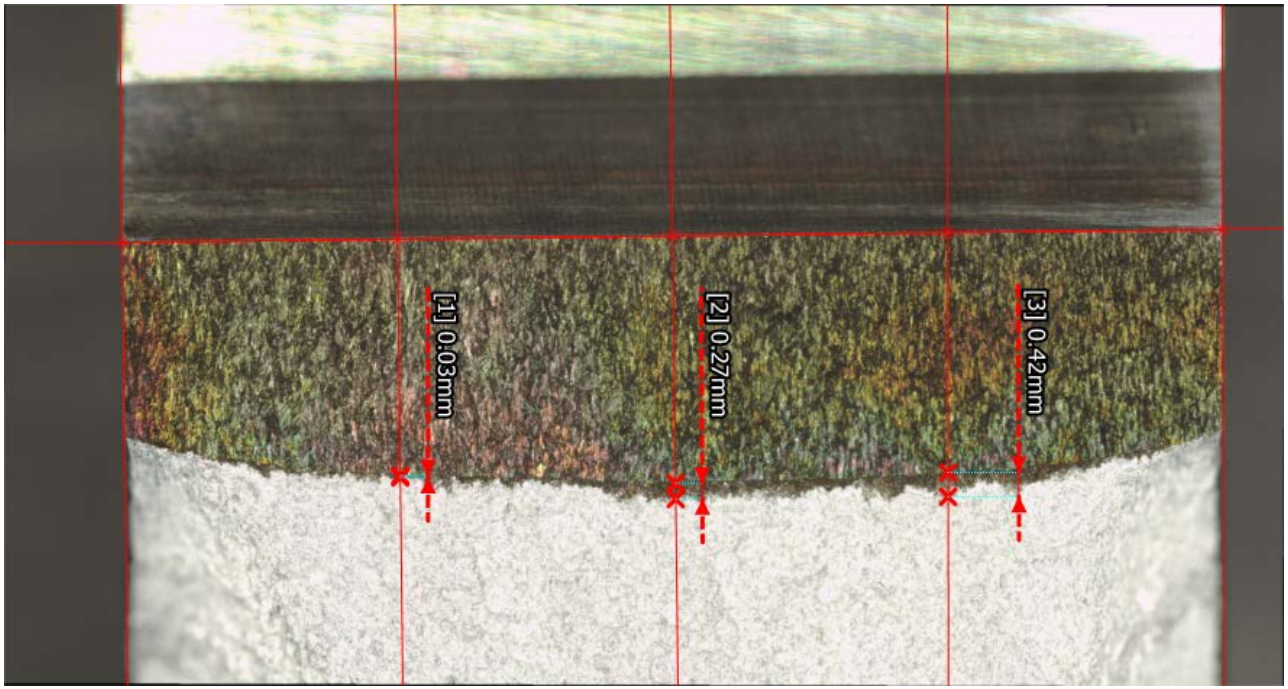


K_{Isi} Method

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

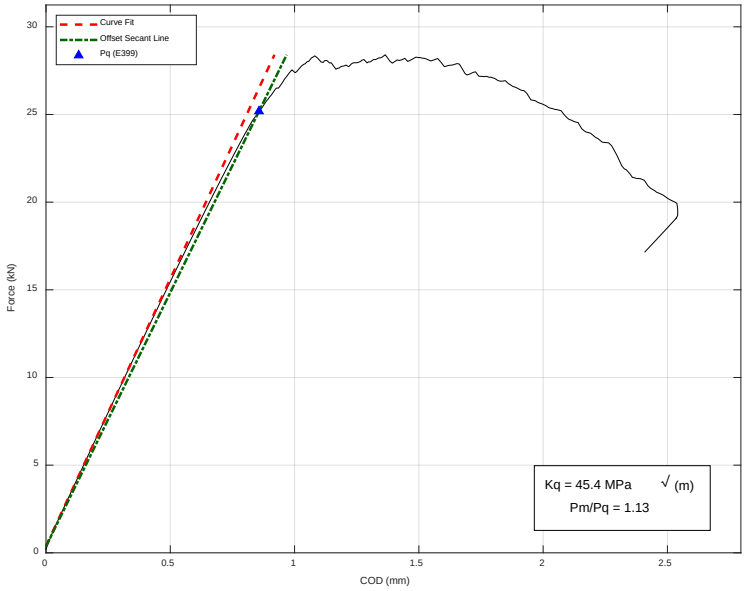
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	14.242	41.6	---	1.63	Not Valid
K_{Isi}	15.324	44.8	---	1.41	Not Valid

K-15-2-8 – Fracture Surface

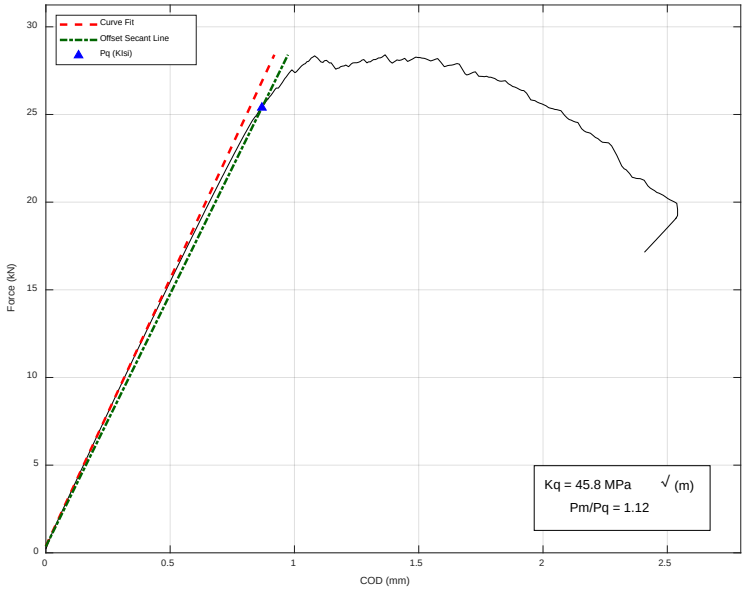


Average crack extension: 0.24 mm

K-2-2-5 - E399 Test



K_{Ic} Method

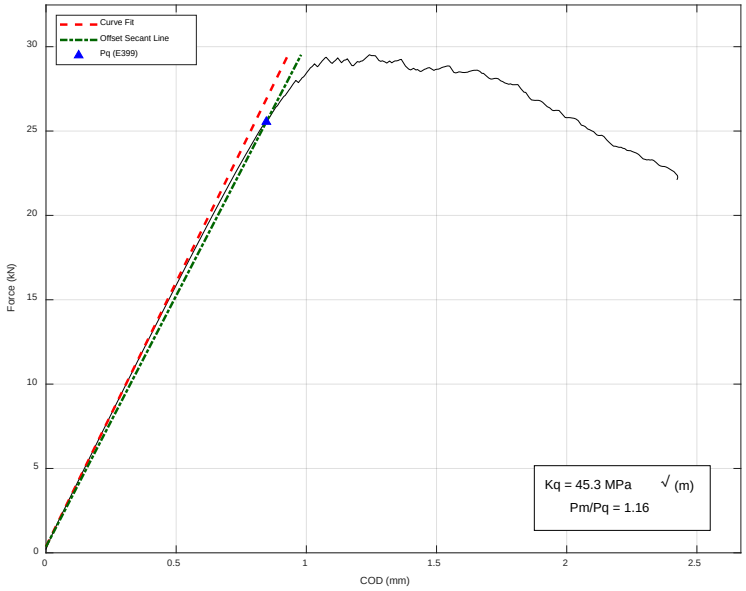


K_{Isi} Method

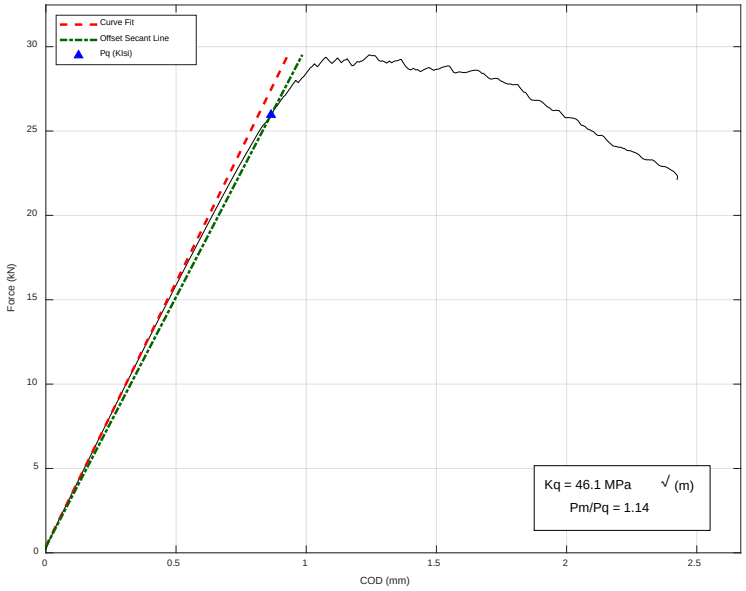
W = 50.8 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.5 mm
$M_{k,limit}$ (K_{Isi}) = 1.95

	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	P_{max}/P_q, Ligament
K_{Isi}	25.390	45.8	1.12	1.86	Ligament

K-2-2-10 - E399 Test



K_{Ic} Method

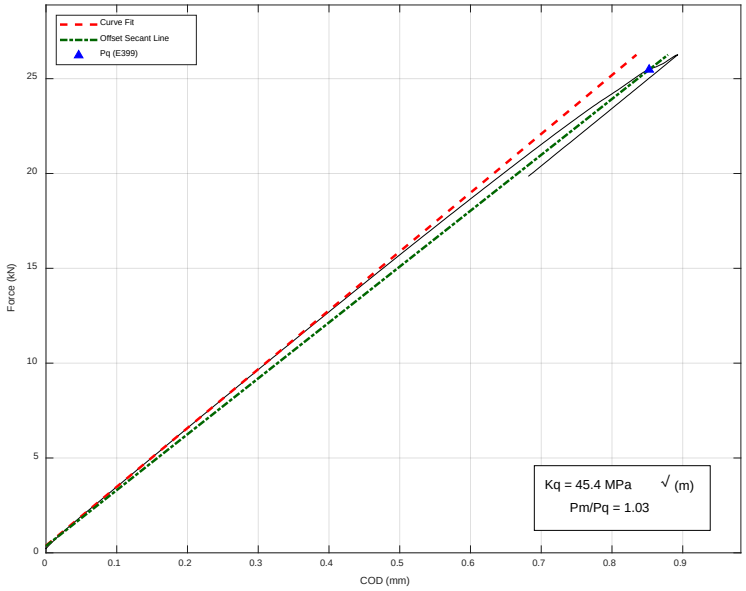


K_{Isi} Method

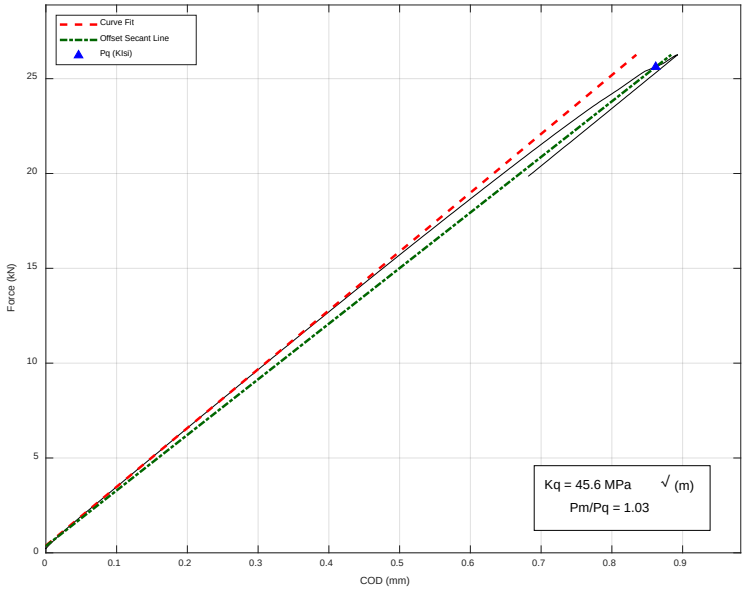
W = 50.8 mm
B = 25.4 mm
B_n = 25.4 mm
a = 26.2 mm
$M_{k,limit}$ (K_{Isi}) = 1.97

	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	P_{max}/P_q, Ligament
K_{Isi}	25.962	46.1	1.14	1.85	Ligament

K-2-2-1 - Interrupted Test



K_{Ic} Method

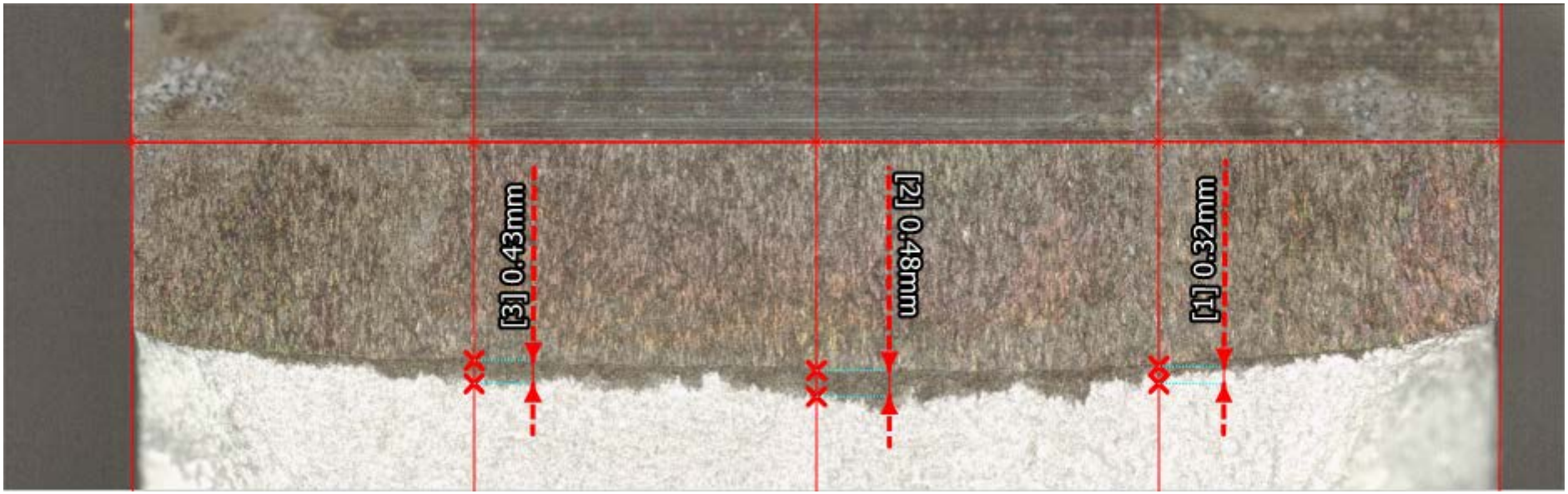


K_{Isi} Method

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

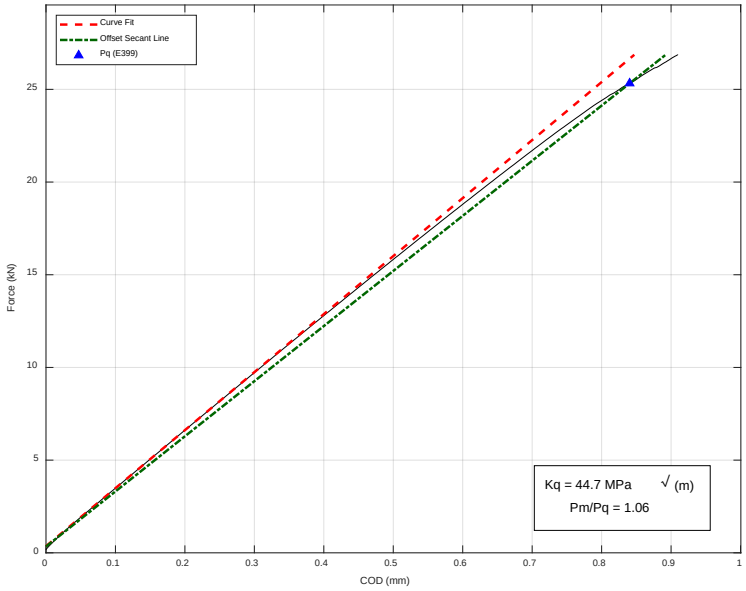
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	25.475	45.4	---	1.91	Not Valid
K_{Isi}	25.619	45.6	---	1.88	Not Valid

K-2-2-1 – Fracture Surface

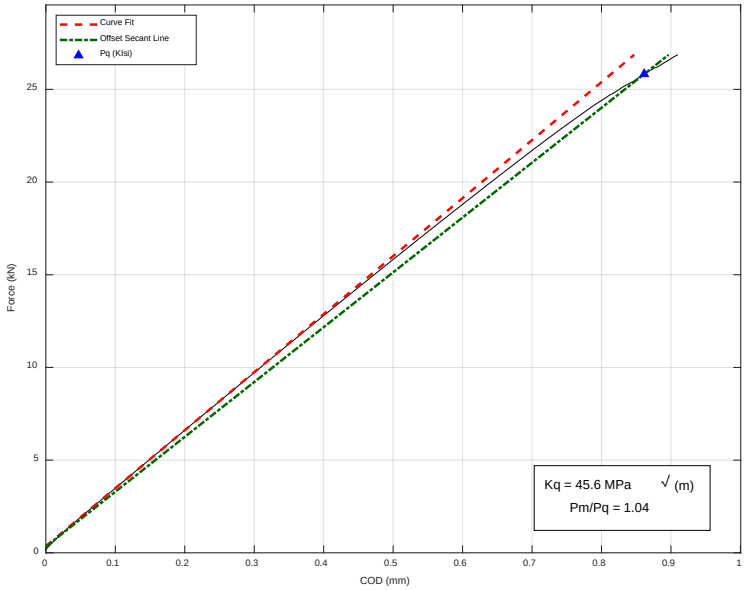


Average crack extension: 0.41 mm

K-2-2-8 - Interrupted Test



K_{Ic} Method

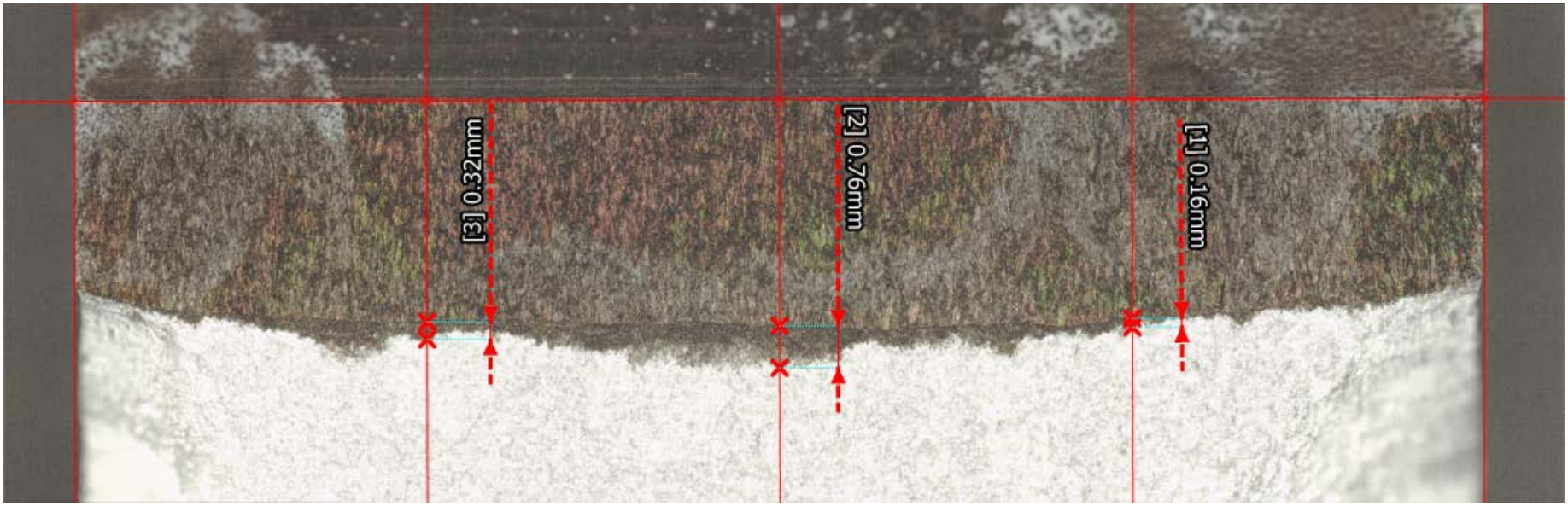


K_{Isi} Method

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

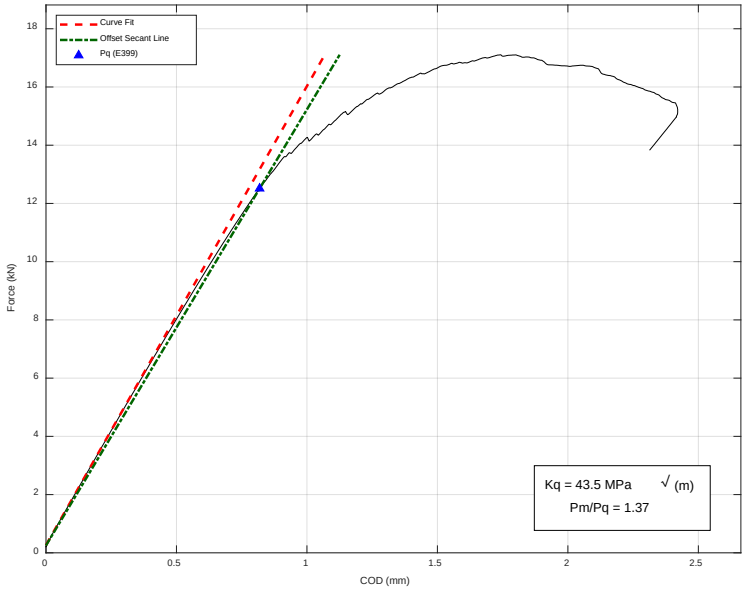
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	25.323	44.7	---	1.98	Not Valid
K_{Isi}	25.824	45.6	---	1.90	Not Valid

K-2-2-8 – Fracture Surface

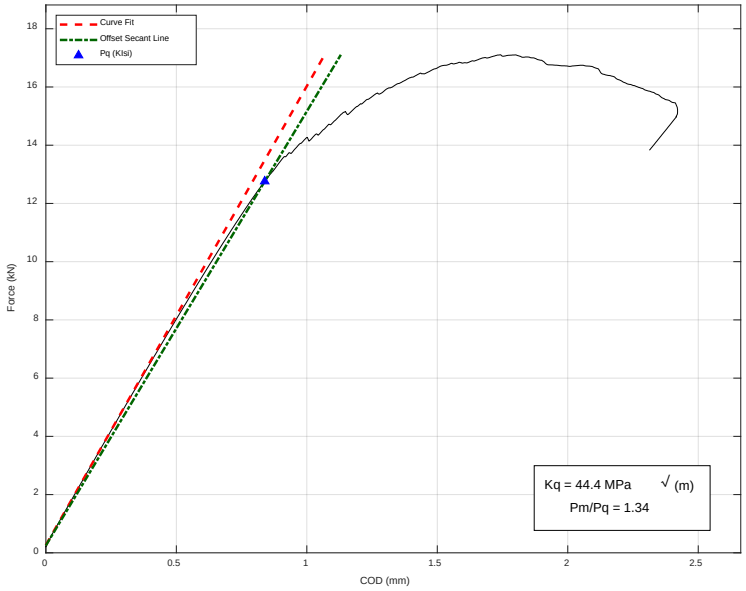


Average crack extension: 0.41 mm

K-2-4-7 - E399 Test



K_{Ic} Method

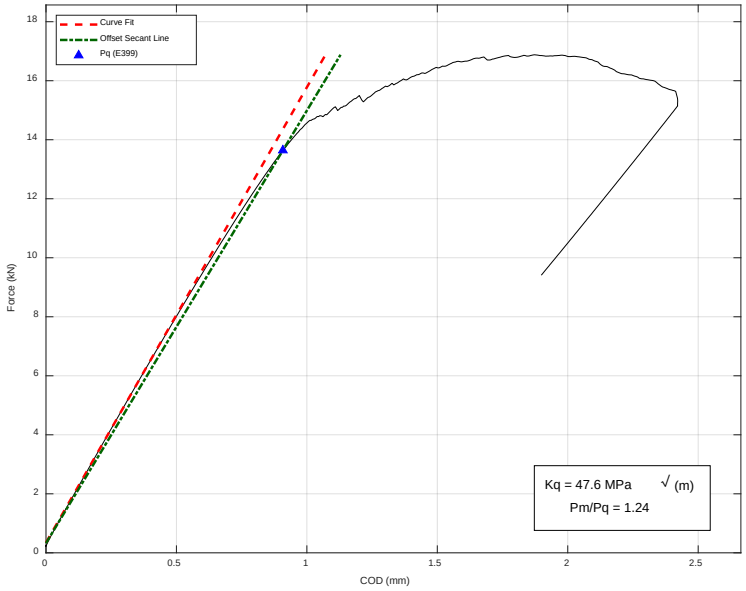


K_{Isi} Method

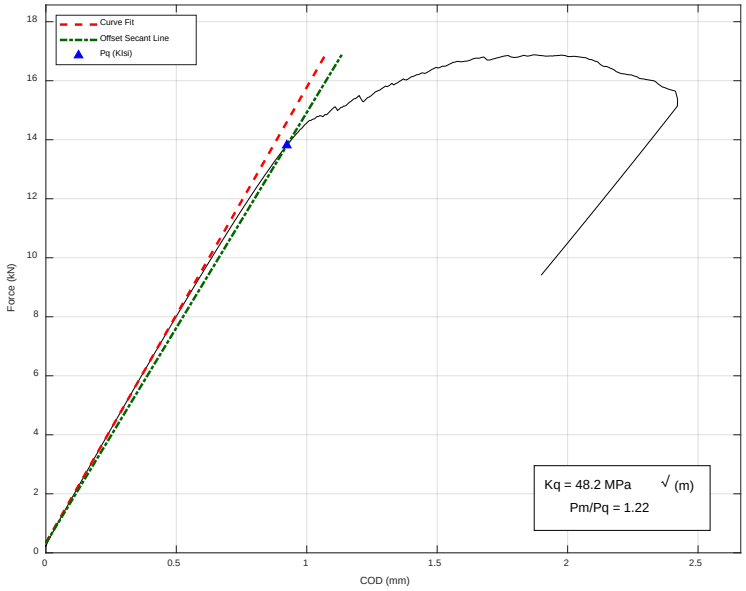
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 25.9 mm
$M_{K,limit}$ (K_{Isi}) = 2.00

	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	P_{max}/P_q, Ligament
K_{Isi}	12.758	44.4	1.34	2.03	Valid

K-2-4-10 - E399 Test



K_{Ic} Method

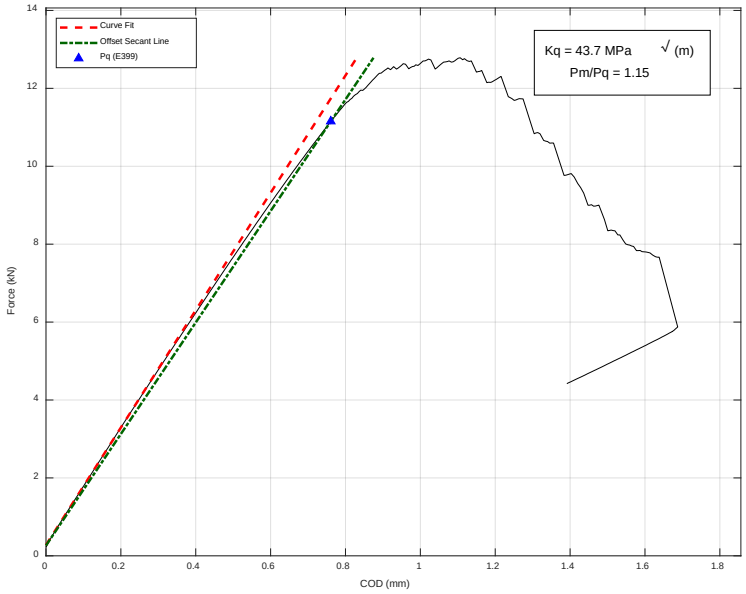


K_{Isi} Method

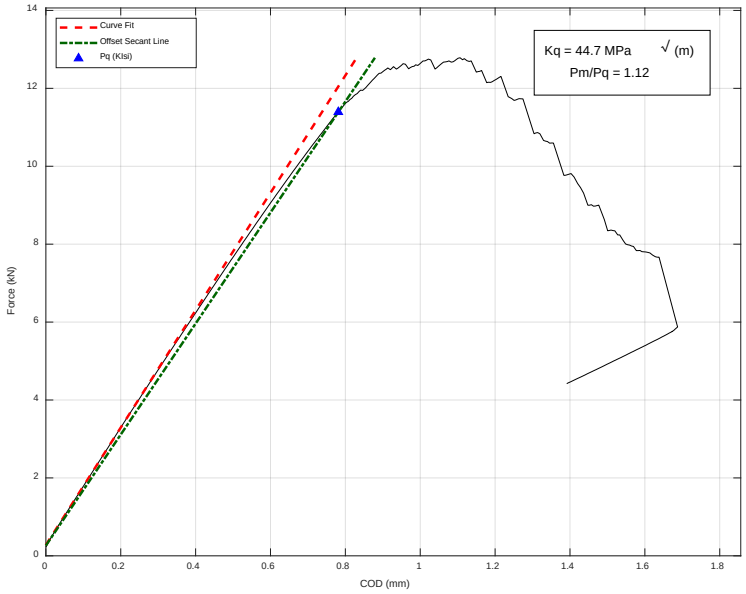
W = 50.8 mm
B = 12.6 mm
B_n = 12.6 mm
a = 25.9 mm
$M_{k,limit}$ (K_{Isi}) = 1.99

	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	P_{max}/P_q, Ligament
K_{Isi}	13.809	48.2	1.22	1.72	Ligament

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



K_{Ic} Method

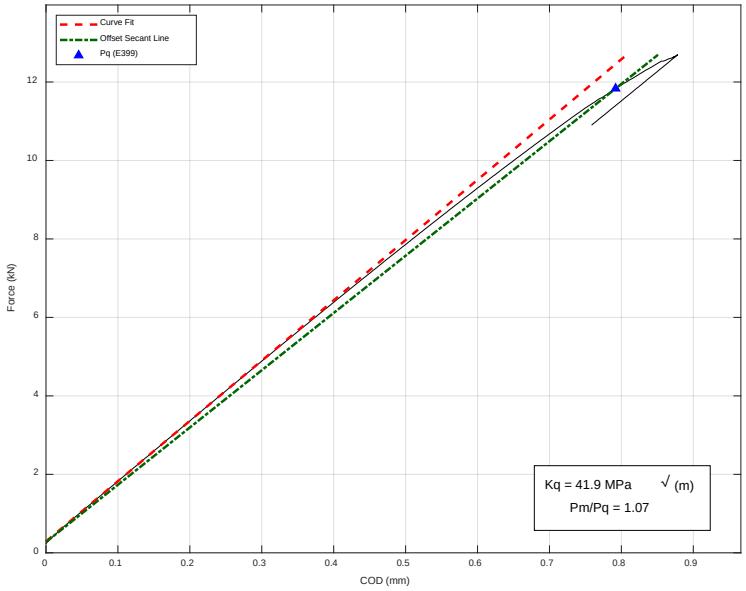


K_{Isi} Method

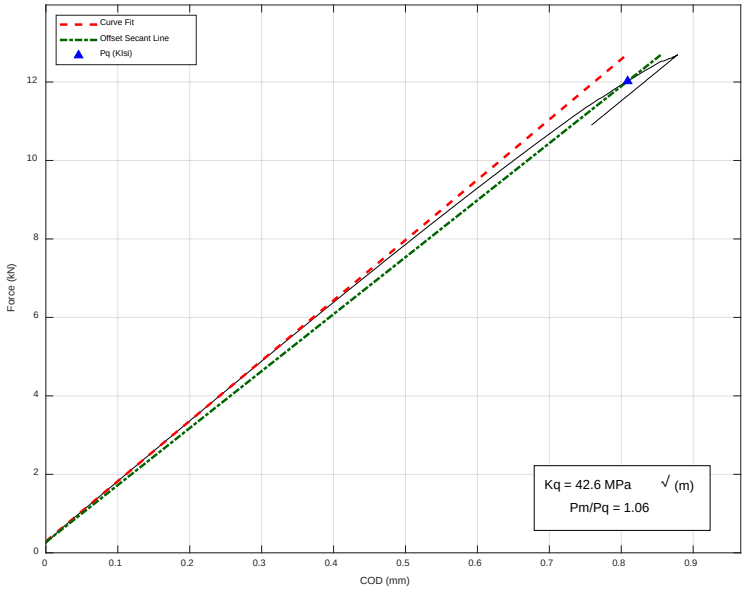
W = 50.9 mm
B = 12.7 mm
B_n = 10.1 mm
a = 26.0 mm
$M_{k,limit}$ (K_{Isi}) = 1.99

	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	P_{max}/P_q, Ligament
K_{Isi}	11.392	44.7	1.12	1.99	Valid

K-2-4-6 - Interrupted Test



K_{Ic} Method

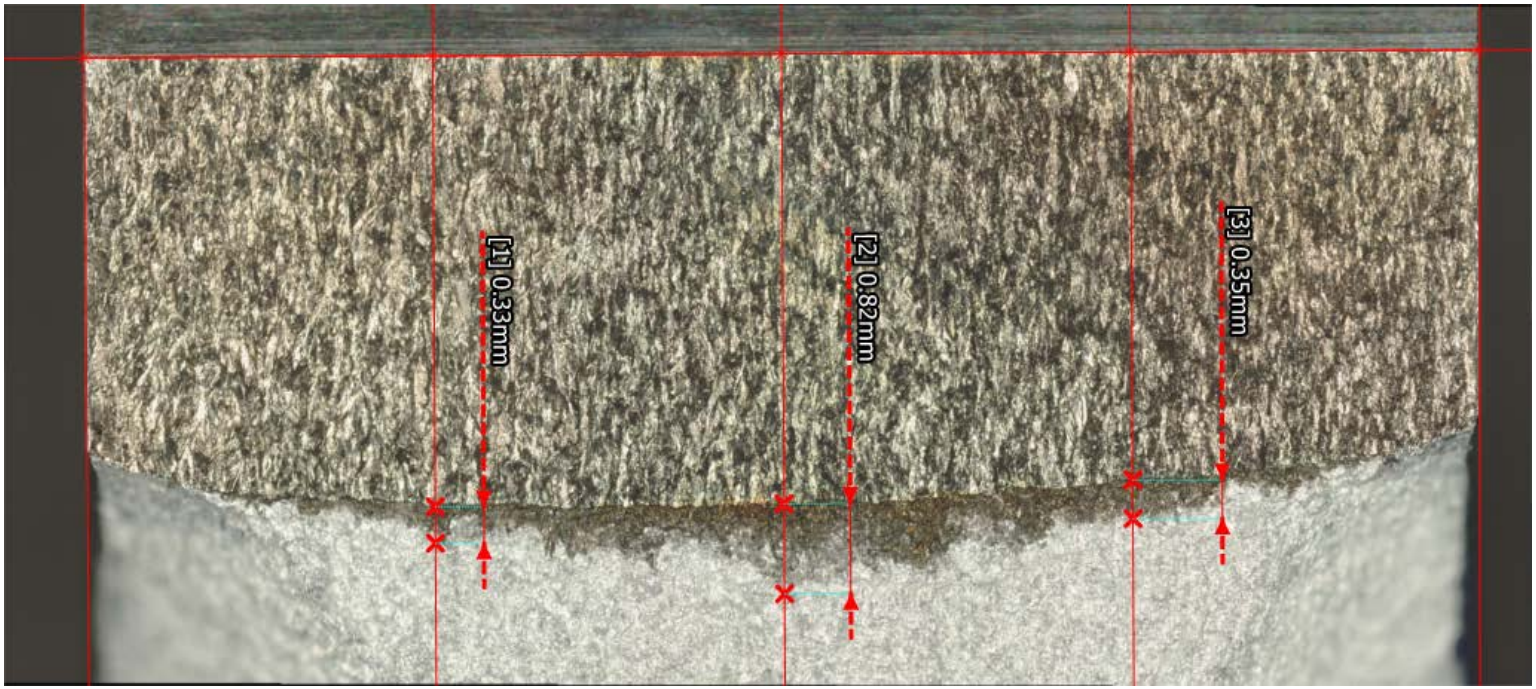


K_{Isi} Method

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

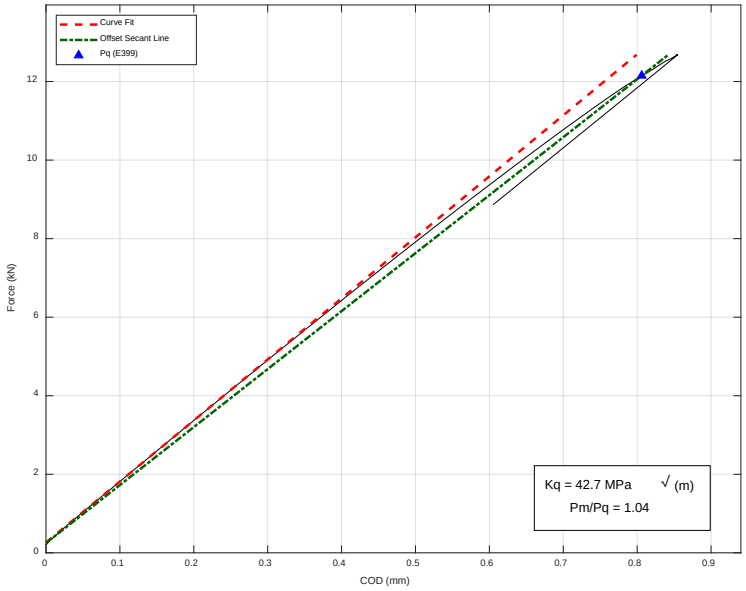
	P_q (kN)	K_q (MPa√m)	P_{max}/P_q	M_K @ K_q	Lig. Validity
K_{Ic}	11.833	41.9	---	2.25	Not Valid
K_{Isi}	12.021	42.6	---	2.18	Valid

K-2-4-6 – Fracture Surface

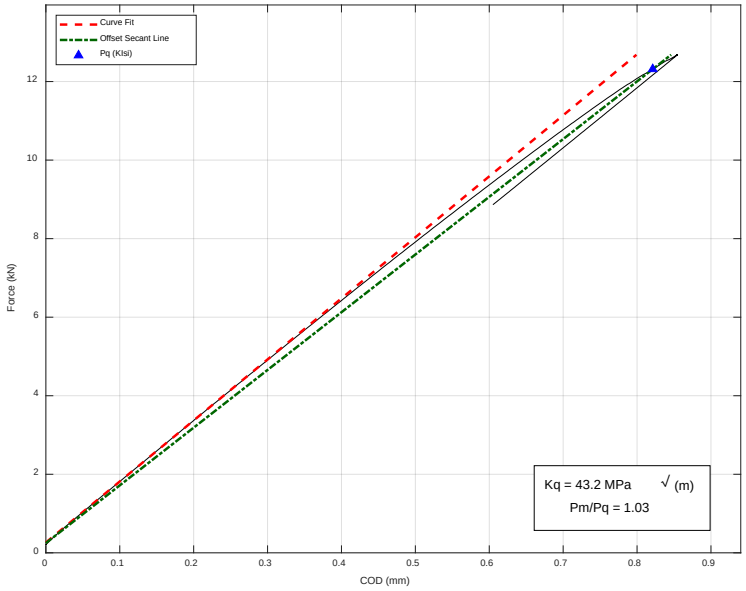


Average crack extension: 0.50 mm

K-2-4-8 - Interrupted Test



K_{Ic} Method

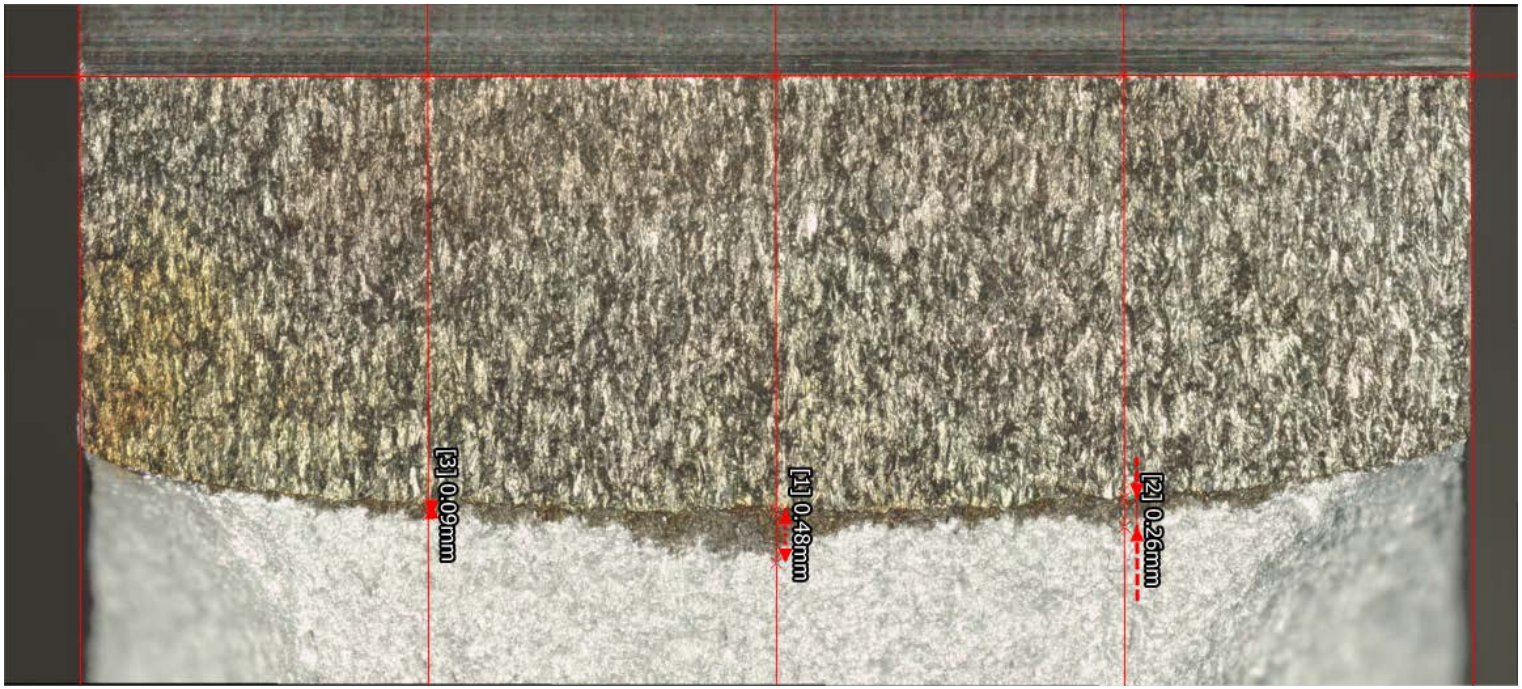


K_{Isi} Method

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



Average crack extension: 0.28 mm