دانشگاه صنعتی اصفهان

دانشکده مکانیک

Fracture Toughness Testing

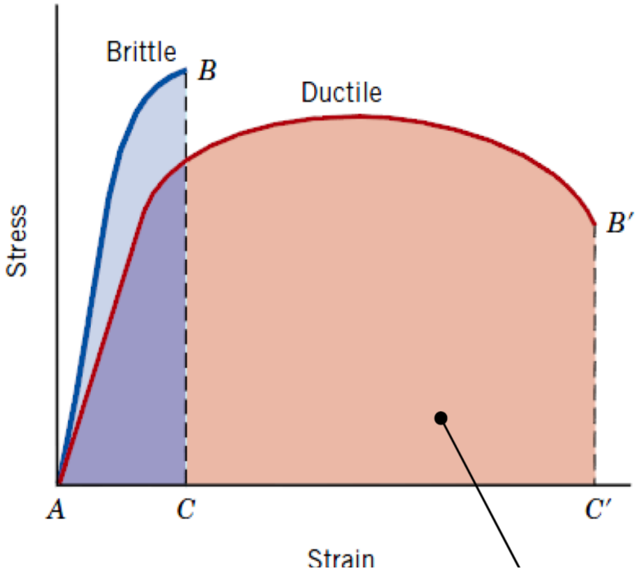
Fracture Toughness

- Toughness is NOT Fracture Toughness

- Plain specimen:

Toughness is the energy (per unit volume) absorbed before final fracture:

- No notch
- No stress concentration



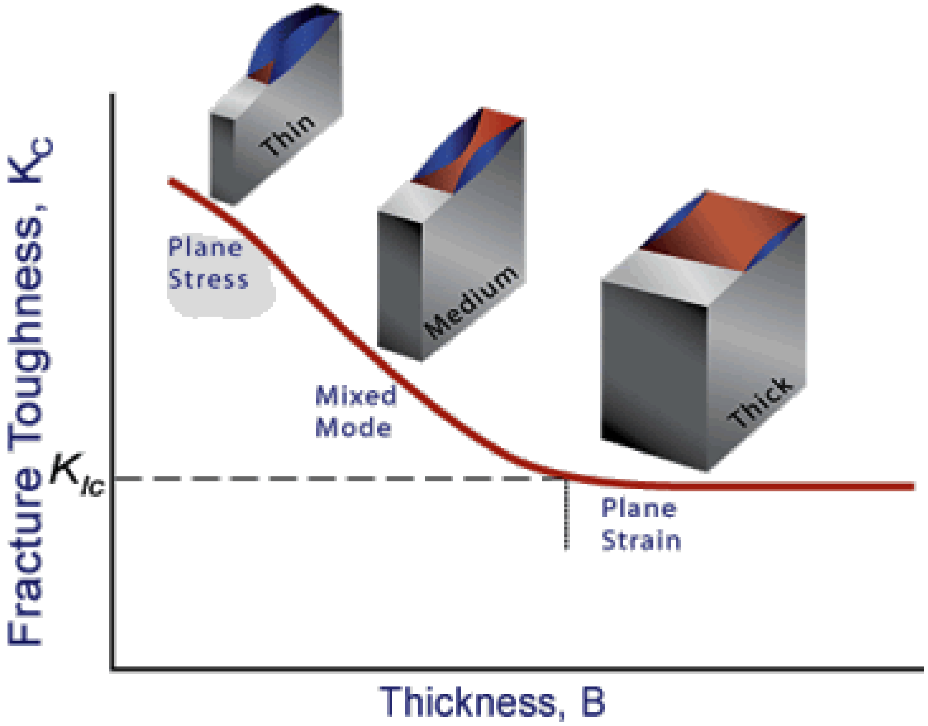
Area: $\sigma\,\varepsilon$ = Energy density

Toughness usually is a trade-off between Strength and Ductility

Fracture Toughness

Is fracture toughness a purely material property?

It is a matter of fact that the Fracture Toughness depends on the specimen thickness. Apparently the explanation is: Pl. Stress/ Pl. Strain

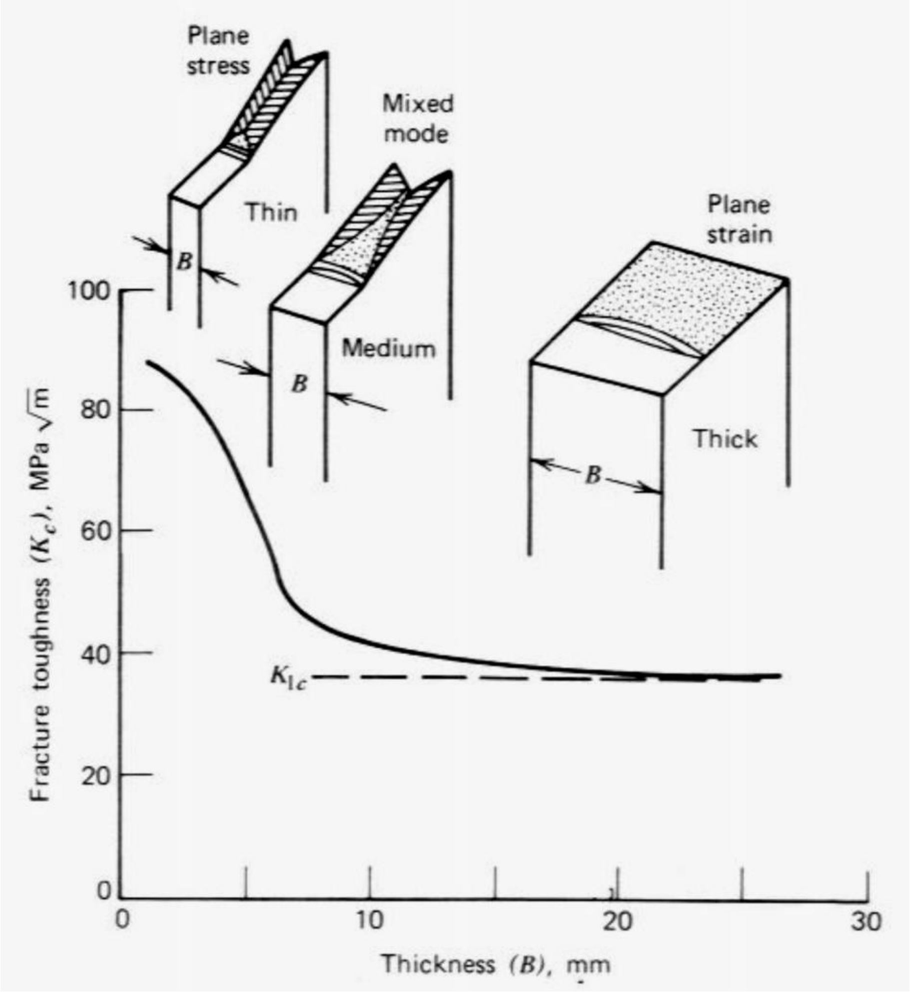


A thicker specimen shows lower Toughness (though the total force for fracture may be higher).
Under pl. strain conditions the plastic volume is less and then the absorbed energy.

Fracture Toughness

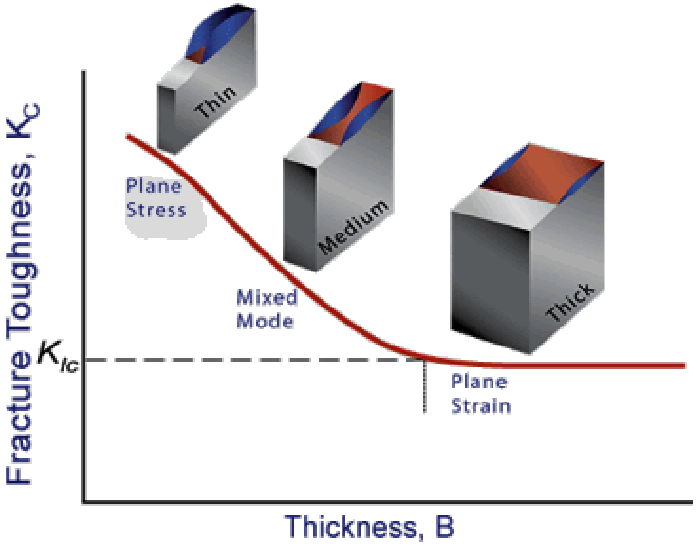
Thickness dependence Pl. Stress/ Pl. Strain Fracture Toughness

45° fracture is usual under Pl. Stress
or at least not well developed Pl. Strain



Fracture Toughness

High thickness (Pl. Strain) Fracture Toughness



The high thickness fracture section is mainly perpendicular to the load, that’s why the ‘I’ (first) is added to the fracture toughness symbol

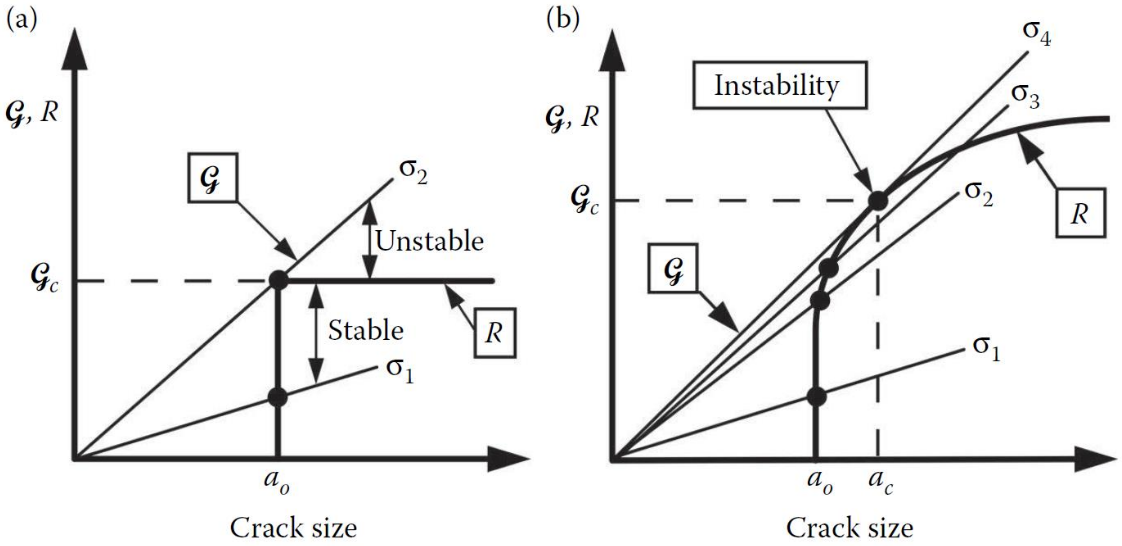
Large thickness:

$K_c \longrightarrow K_{Ic}$

K_{Ic} is a material property only!
no more dependent on thickness
or any other geometry parameter

Fracture Toughness

- A fracture toughness test measures the resistance of a material to crack extension. Such a test may yield either a single value of fracture toughness or a resistance curve, where a toughness parameter such as K, J, or CTOD is plotted against crack extension.
- A single toughness value is usually sufficient to describe a test that fails by cleavage, because this fracture mechanism is typically unstable. The situation is similar to the schematic in following figure, which illustrates a material with a flat R curve.



Fracture Toughness

- A variety of organizations throughout the world publish standardized procedures for fracture toughness measurements, including the American Society for Testing and Materials (ASTM), the British Standards Institution (BSI), the International Organization for Standardization (ISO), and the Japan Society for Mechanical Engineers (JSME). The first standards for K and J testing were developed by ASTM in 1970 and 1981, respectively, while BSI published the first CTOD test method in 1979.

- Existing fracture toughness standards include procedures for K_{Ic}, K–R curve, J_{Ic}, J–R curve, CTOD testing.

General Considerations

- The majority of fracture toughness tests have several common features. The design of test specimens is similar in most of the standards, and the orientation of the specimen relative to symmetry directions in the material is always an important consideration. The cracks in test specimens are introduced by fatigue in each case, although the requirements for fatigue loads vary from one standard to the next.

- The basic instrumentation required to measure load and displacement is common to most fracture mechanics tests, but some tests require additional instrumentation to monitor crack growth.

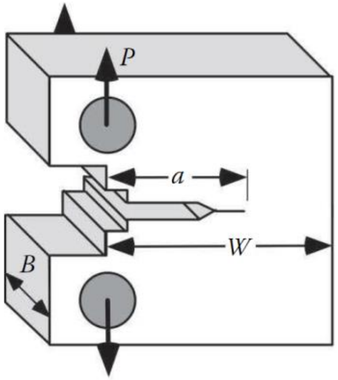
General Considerations

Specimen Configurations

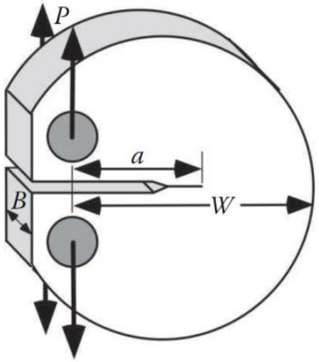
- There are five types of specimens that are permitted in ASTM standards that characterize fracture initiation and crack growth, although no single standard allows all five configurations, and the design of a particular specimen type may vary between standards. The configurations that are currently standardized include the compact tension (C(T)) specimen, the single-edge notched bend (SE(B)) geometry, the arc-shaped specimen, the disk specimen, and the middle tension (MT) panel.

General Considerations

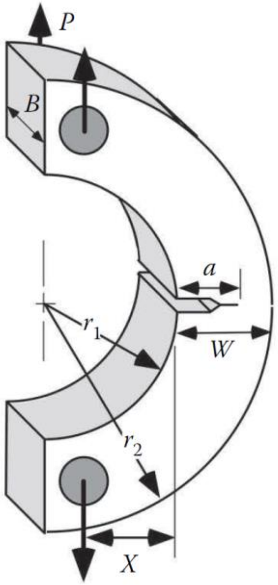
Standardized fracture mechanics test specimens



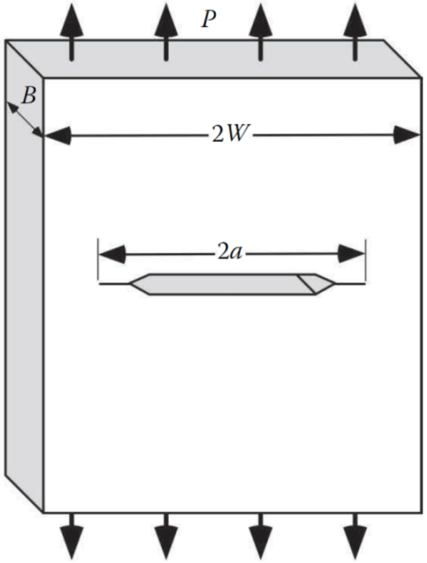
Compact Tension (C(T))



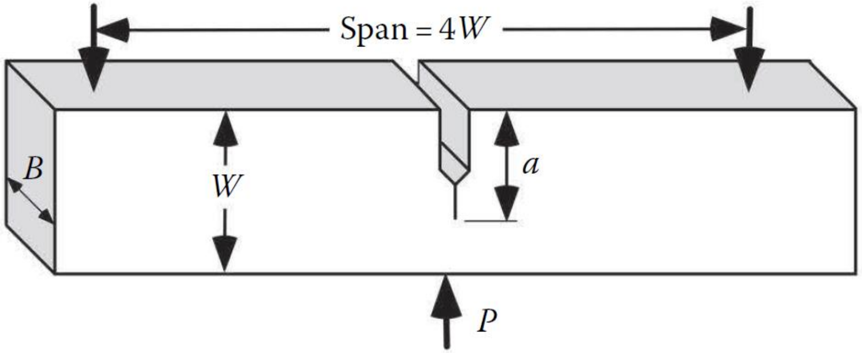
Disk-shaped compact



Arc-shaped specimen



Middle Tension (MT) panel



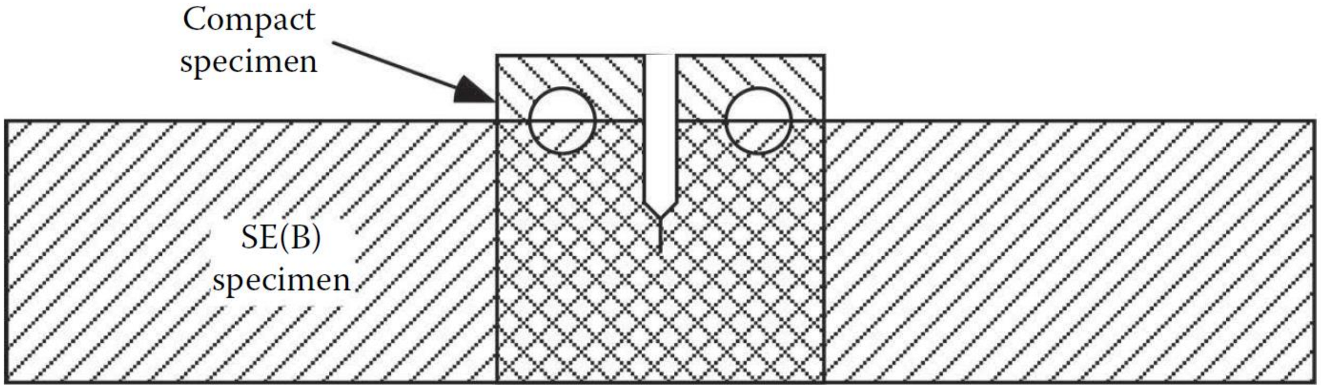
Single-Edge notched Bend (SE(B))

General Considerations

Specimen Configurations

- Each specimen configuration has three important characteristic dimensions: the crack length (a), the thickness (B), and the width (W). In most cases, W = 2B and a/W= 0.5, but there are exceptions which are discussed later.

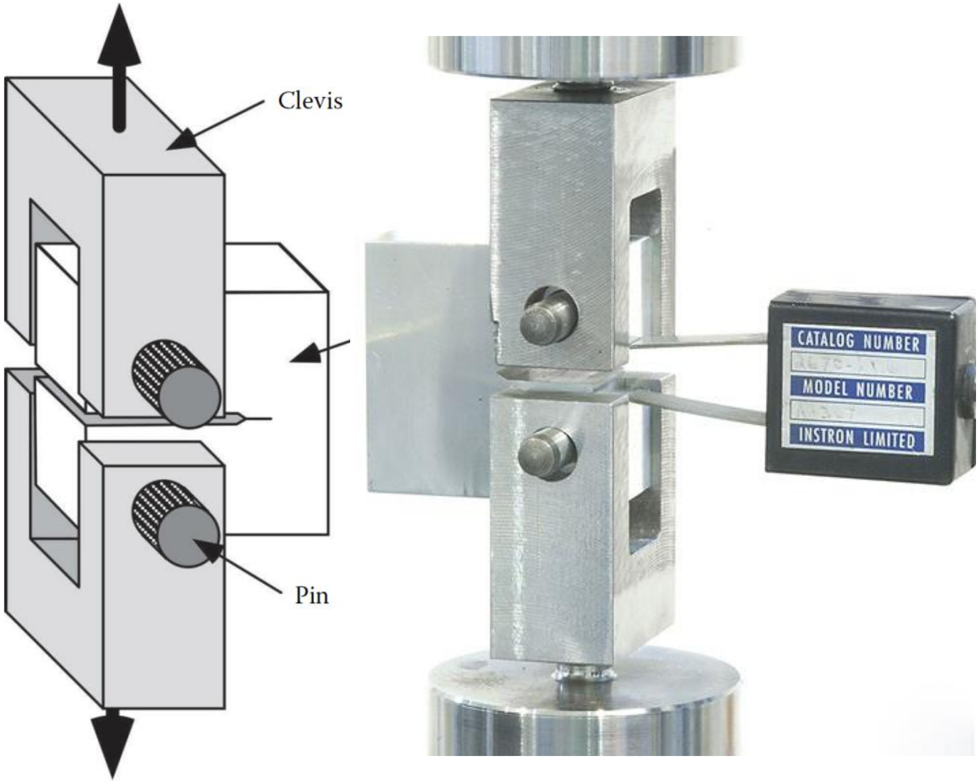
- The vast majority of fracture toughness tests are performed on either C(T) or SE(B) specimens.



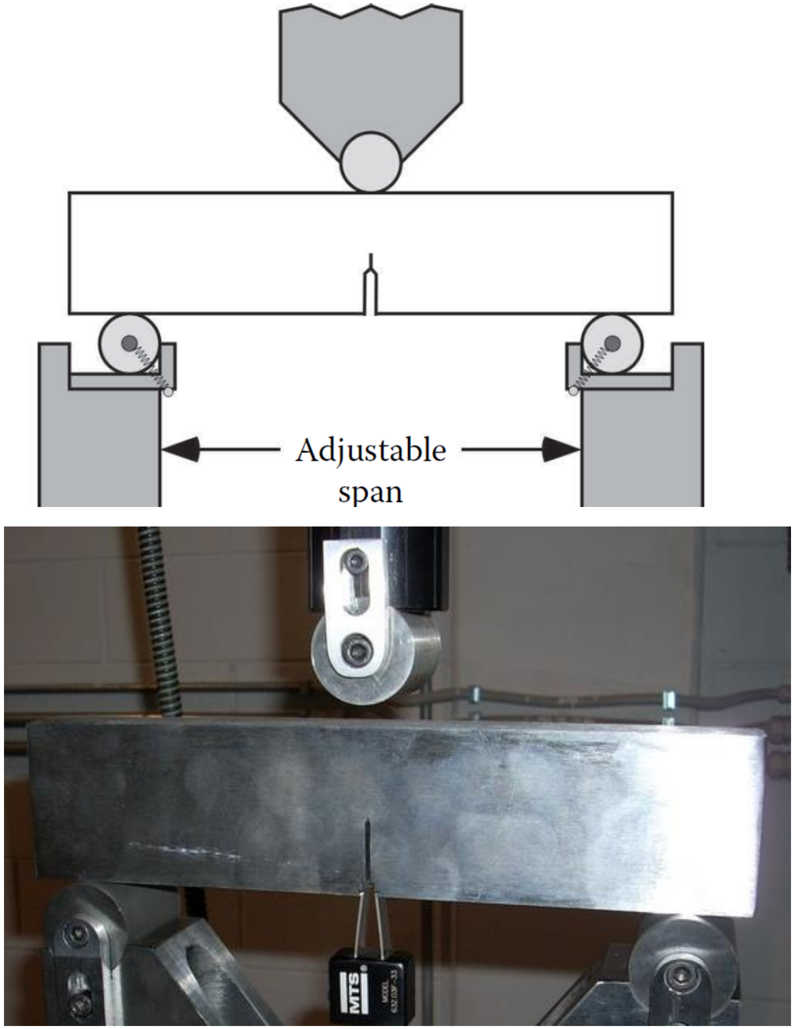
Comparison of the profiles of C(T) and SE(B) specimens with the same in-plane characteristic dimensions (W and a).

General Considerations

Specimen Configurations



Apparatus for testing C(T) specimens.



Three-point bending apparatus for testing SE(B) specimens.

General Considerations

Specimen Orientation

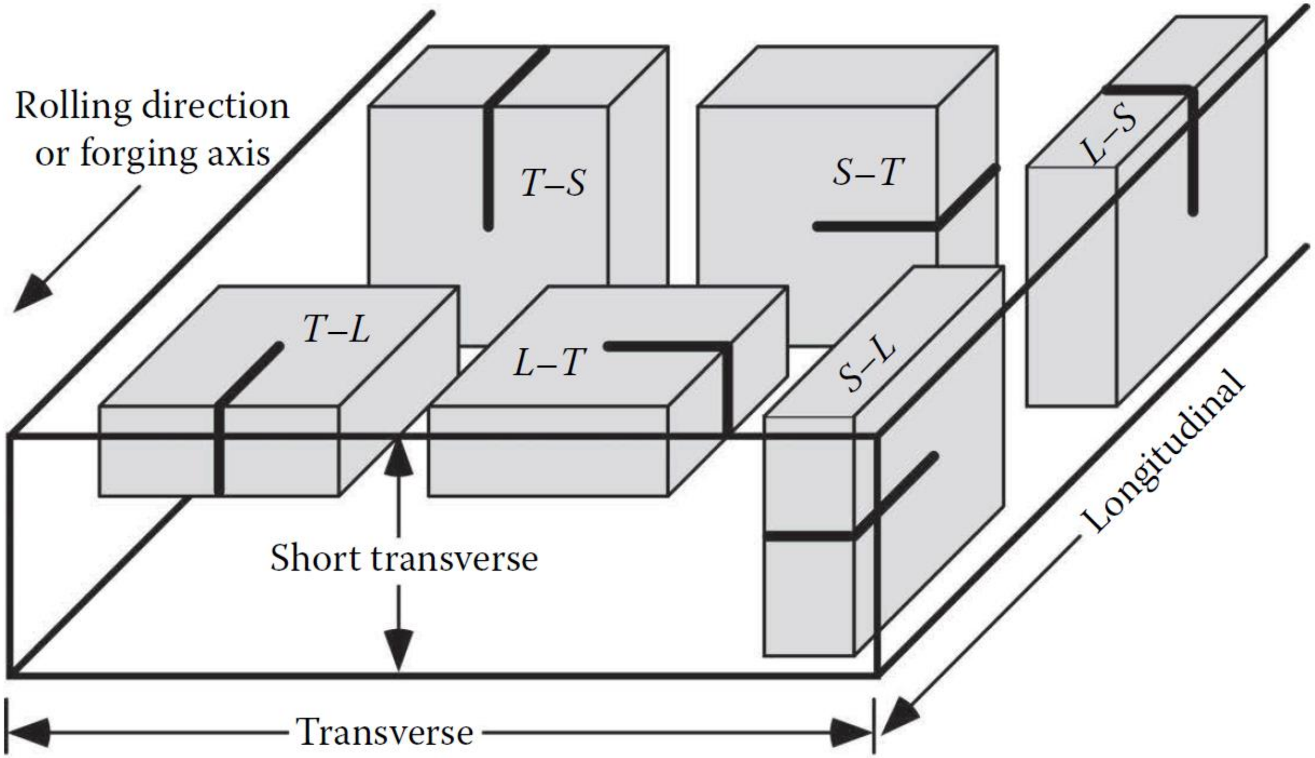
- Engineering materials are seldom homogeneous and isotropic. Microstructures, and thus mechanical properties, are often sensitive to direction. The sensitivity to orientation is particularly pronounced in fracture toughness measurements, because a microstructure with a preferred orientation may contain planes of weakness, where crack propagation is relatively easy. Since specimen orientation is such an important variable in fracture toughness measurements, all ASTM fracture testing standards require that the orientation be reported along with the measured toughness.

- When the specimen is aligned with the axes of symmetry in the plate, there are six possible orientations. The letters L, T, and S denote the longitudinal, transverse, and short transverse directions, respectively, relative to the rolling direction or forging axis.

General Considerations

Specimen Orientation

- Note that two letters are required to identify the orientation of a fracture mechanics specimen; the first letter indicates the direction of the principal tensile stress, which is always perpendicular to the crack plane in Mode I tests, and the second letter denotes the direction of crack propagation.

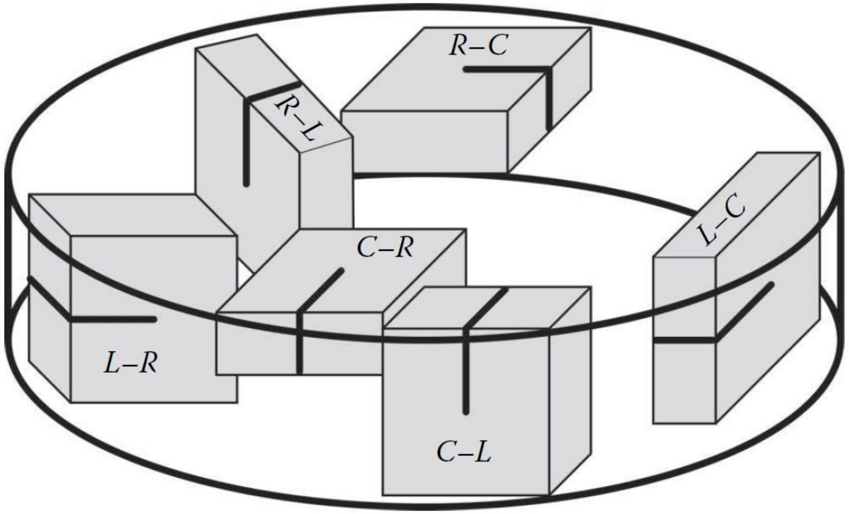


ASTM notation for specimens extracted from rolled plate and forgings.

General Considerations

Specimen Orientation

- Ideally, one should measure the toughness of a material in several orientations, but this is often not practical. When choosing an appropriate specimen orientation, one should bear in mind the purpose of the test, as well as the geometrical constraints imposed by the material. A low toughness orientation, where the crack propagates in the rolling direction (T–L or S–L), should be adopted for general material characterization or screening. When the purpose of the test is to simulate conditions in a flawed structure, however, the crack orientation should match that of the structural flaw. Geometrical constraints may preclude testing some configurations; the S–L and S–T orientations.

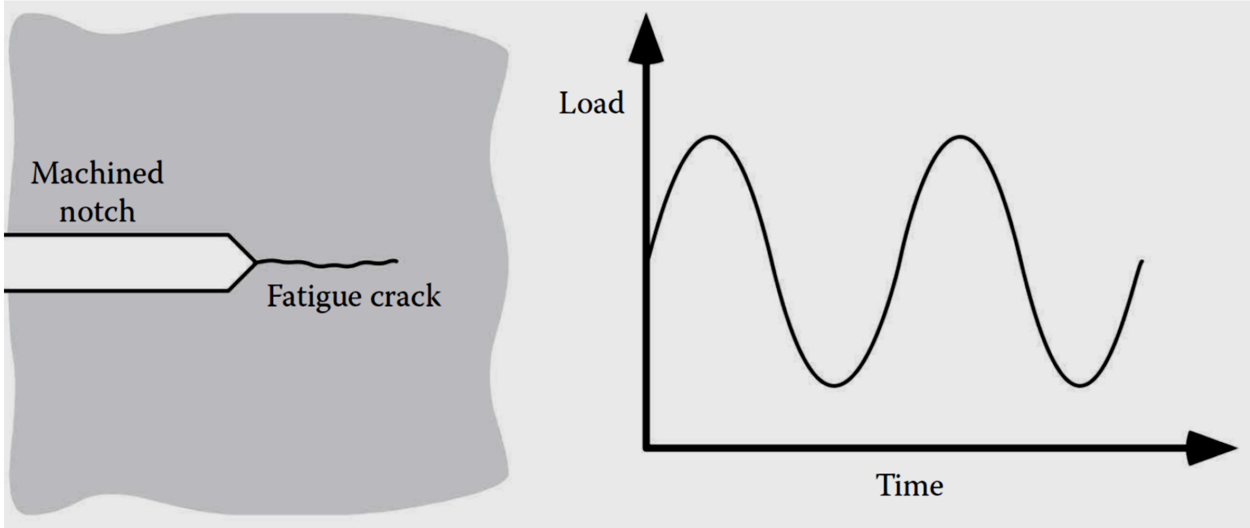


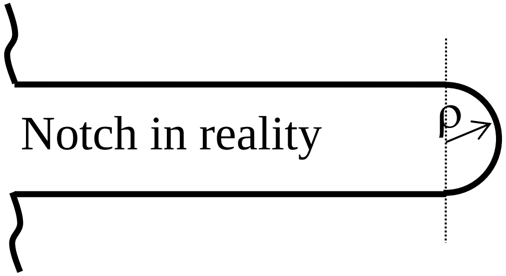
ASTM notation for specimens extracted from disks and hollow cylinders.

General Considerations

Fatigue Precracking

- Fracture mechanics theory applies to cracks that are infinitely sharp prior to loading. While laboratory specimens invariably fall short of this ideal, it is possible to introduce cracks that are sufficiently sharp for practical purposes. The most efficient way to produce such a crack is through cyclic loading.
  - The theory considers an ideal plane crack with *zero* notch radius $\rho \to 0$





General Considerations

Fatigue Precracking

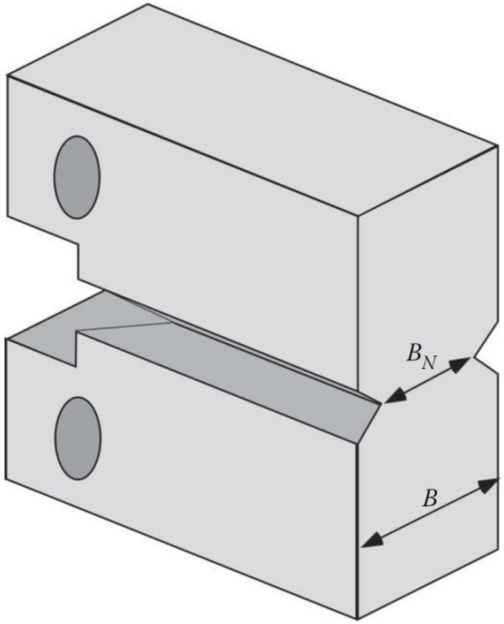
- The fatigue crack must be introduced in such a way as not to adversely influence the toughness value that is to be measured. Cyclic loading produces a crack of finite radius with a small plastic zone at the tip, which contains strain hardened material and a complicated residual stress distribution. In order for a fracture toughness to reflect true material properties, the fatigue crack must satisfy the following conditions:

- The crack tip radius at failure must be much larger than the initial radius of the fatigue crack.
- The plastic zone produced during fatigue cracking must be small compared to the plastic zone at fracture.

General Considerations

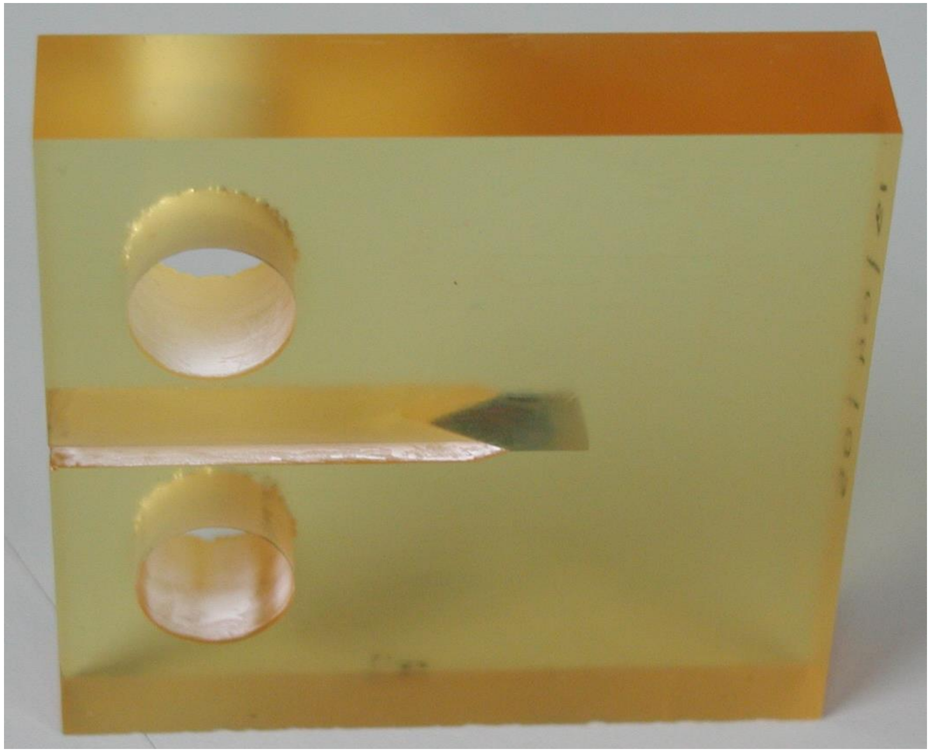
Side Grooving

- In certain cases, grooves are machined into the sides of fracture toughness specimens. The primary purpose of side grooving is to maintain a straight crack front during an R-curve test. A specimen without side grooves is subject to crack tunneling and shear lip formation because the material near the outer surfaces is in a state of low stress triaxiality.
- Side grooves remove the free surfaces, where plane stress conditions prevail and, if done properly, lead to relatively straight crack fronts. Typical side-grooved fracture toughness specimens have a net thickness that is approximately 80% of the gross thickness. If the side grooves are too deep, they produce lateral singularities, which cause the crack to grow more rapidly at the outer edges.



K_{Ic} Testing

Experimental determination of K_{IC}



- Fracture Toughness K_{Ic}
  - Plane strain condition
  - ASTM standard E399

ASTM : **A**merican **S**ociety of **T**esting and **M**aterials

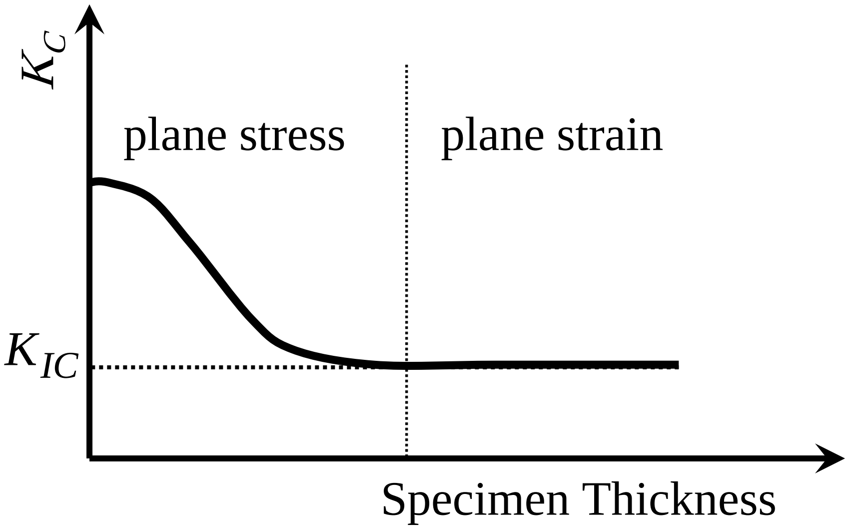
K_{Ic} Testing

Introduction:

Assuming a *small plastic zone* compared to the specimen dimensions,

a critical value of the mode-I SIF may be an appropriate fracture parameter .

K_{IC} : plane strain fracture toughness



K_C : critical SIF, depends on thickness

$K_I > K_C$: crack propagation

K_{IC} : Lower limiting value of fracture toughness K_C

Material constant for a specific temperature and loading speed

K_{Ic} Testing

- ASTM **E 399** first standardized test method for K_{IC} :

  - was originally published in 1970

  - is intended for *metallic* materials

  - has undergone a number of revisions over the years

  - gives specimen size requirements to ensure measurements in the *plateau* region

- ASTM **D 5045 -99** is used here for *plastic* materials:

Standard Test Methods for Plane-Strain Fracture Toughness and
Strain Energy Release Rate of Plastic Materials

Many similarities to E 399, with additional specifications important for plastics.

- K_I based test method ensures that the specimen fractures under linear elastic conditions

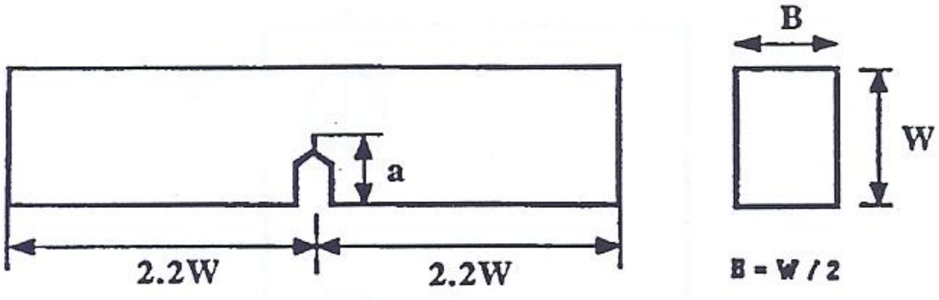
↳ confined plastic zone at the crack tip

K_{Ic} Testing

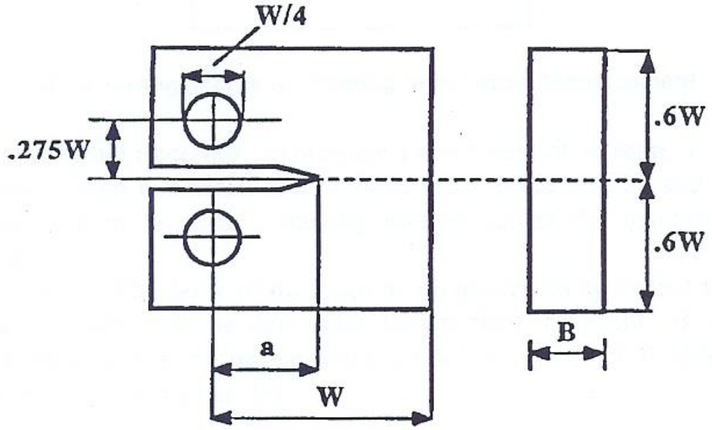
1- Test specimens

Two specimen configurations:

- Three Point Bend specimen (SENB):



- Compact tension configuration (CT):



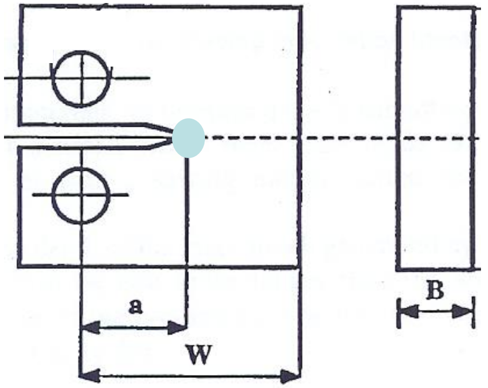
$$2 \le W/B \le 4$$

$$0.45 \le a/W \le 0.55$$

K_{Ic} Testing

For valid K_{IC} measurements, the specimens are designed to ensure :

- a small plastic zone size / specimen thickness B.



Plastic zone length r_y from Irwin Model (plane strain): $r_p = \dfrac{1}{2\pi}\left(\dfrac{K_I}{\sigma_Y}\right)^2$

From ASTM 399 $\begin{cases} \text{Plane stress condition if } r_y = B \\ \text{Plane strain condition if } r_y < B/25 \end{cases}$

$$\text{Thus,} \quad B > \frac{25}{3\pi}\left(\frac{K_I}{\sigma_Y}\right)^2 \approx 2.5\left(\frac{K_I}{\sigma_Y}\right)^2$$

- that plane strain conditions dominate around the crack tip.

$$B \geq 2.5\left(\frac{K_{IC}}{\sigma_Y}\right)^2 \qquad a \geq 2.5\left(\frac{K_{IC}}{\sigma_Y}\right)^2 \qquad W - a \geq 2.5\left(\frac{K_{IC}}{\sigma_Y}\right)^2$$

σ_Y yield stress of the material for the temperature and loading rate of the test

➡ B must be sufficient to ensure plane strain.

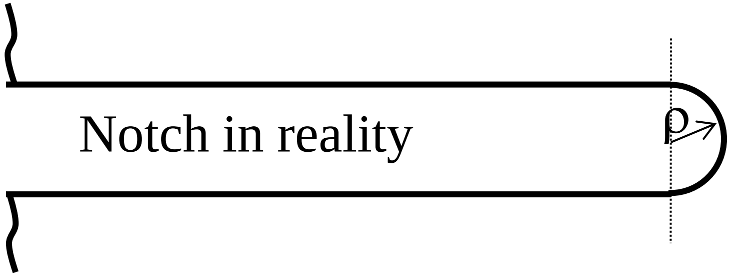
➡ $W\text{-}a$ must be sufficient to avoid excessive plasticity in the ligament.

K_{Ic} Testing

2- Precrack:

- Remark:

The theory considers an ideal plane crack with *zero* notch radius $\rho \rightarrow 0$



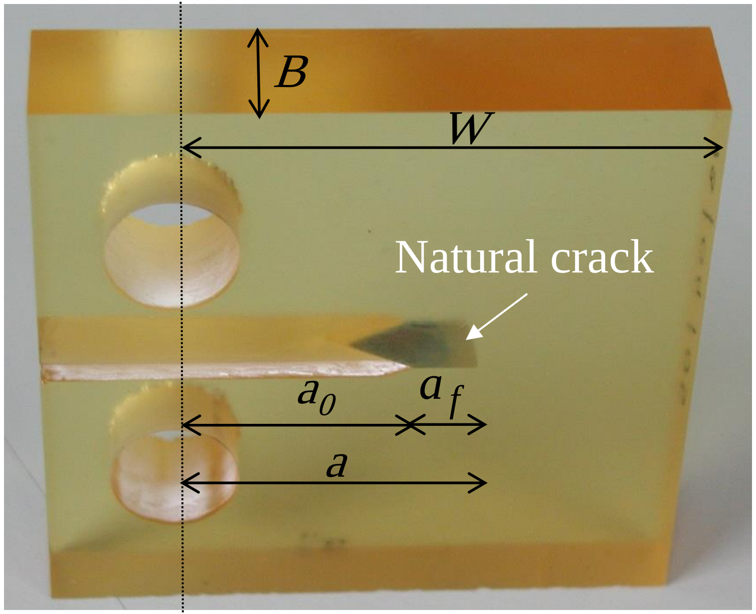
K_C decreases with decreasing ρ until a limiting value $\rho_C \cong 6.3\ \mu\text{m}$

Below ρ_C , K_C approximately constant:

➡ The notch can simulate the theoretical crack

K_{Ic} Testing

- **Chevron starter notch:**



The chevron *forces* crack initiation at its center.

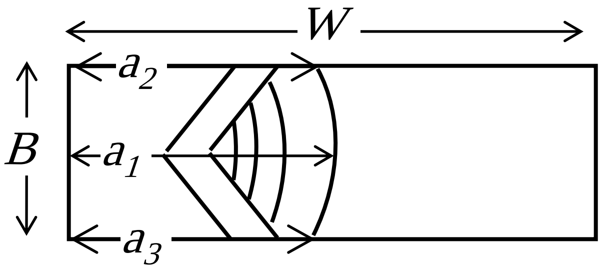
A sharp crack of length a_f is propagated by fatigue such that:

$$0.45 \le a/W \le 0.55 \quad \text{where} \quad a = a_0 + a_f$$

During fatigue the maximum SIF must not exceed 60 % of K_{IC}

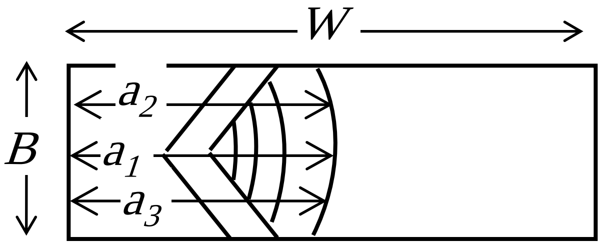
The measured crack length a is the average of the crack lengths measured at:

- the center of the crack front: a_1
- the end of the crack front on each surface: a_2 and a_3



$$a = (a_1 + a_2 + a_3)/3$$

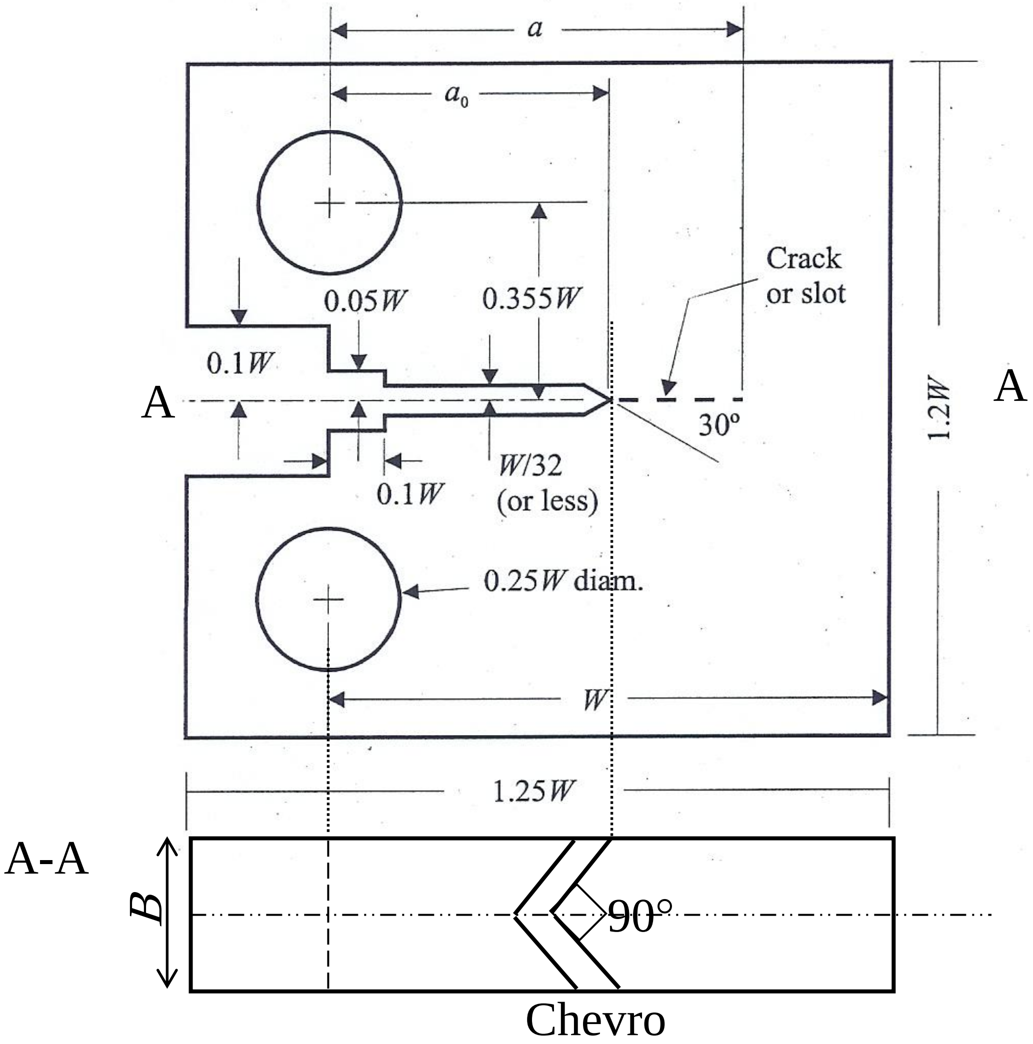
Alternatively,



Measurements of B and W to 0.1% accuracy

K_{Ic} Testing

- Laboratory specifications for the specimen



$W = 48$ mm

$a_0 = 0.45$ W

K_{Ic} Testing

3- Experimental procedure

- Expression for the calculation of the SIF (CT- configuration):

$$K_Q = \frac{P_Q}{BW^{1/2}} f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}}\left(0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.60\left(\frac{a}{W}\right)^4\right)$$

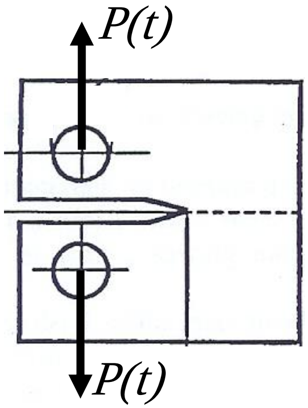
f shape function for the CT specimen

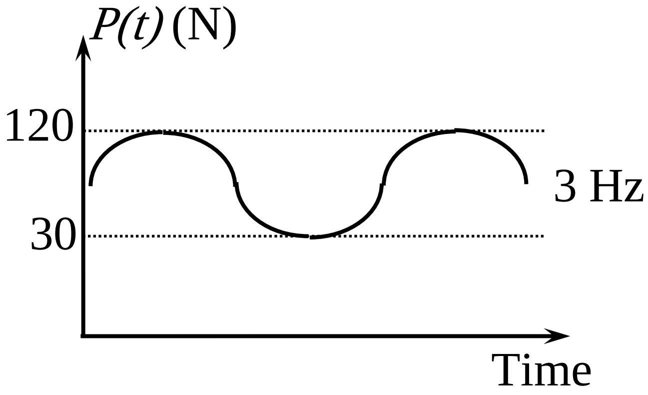
K_Q conditional or trial K_{IC} value.

K_{Ic} Testing

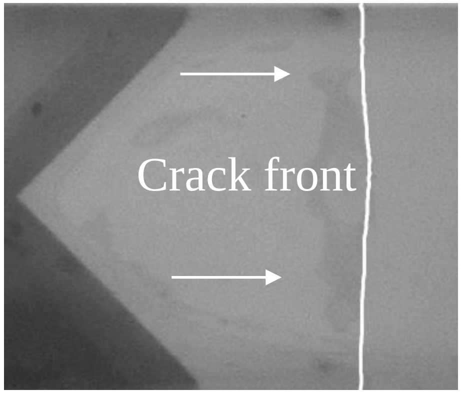
- **Test procedure:**

- Fatigue crack propagation:





≈ half a day to complete



Servohydraulic testing system used with *constant* displacement rate imposed.

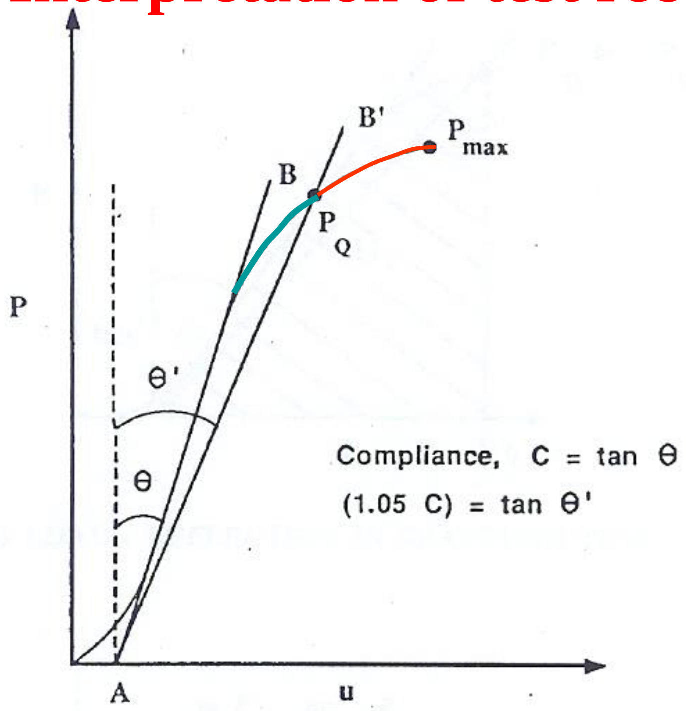
Loading rate and test temperature should be noted.

Both displacement and load recorded simultaneity during the test.

Several specimens tested (at least three) : reproducibility

K_{Ic} Testing

4- Interpretation of test record and calculation of K_{IC}



P_{max} : maximum load sustained by the specimen

AB : initial compliance C = u / P

AB' : compliance 5% greater than AB

Evaluation of P_Q :

P_{max} *within* lines (AB) and (AB'): $P_Q = P_{max}$ ➡ Calculus of K_Q

P_{max} *outside* lines (AB) and (AB'): P_Q = intersection of (AB') and the load curve

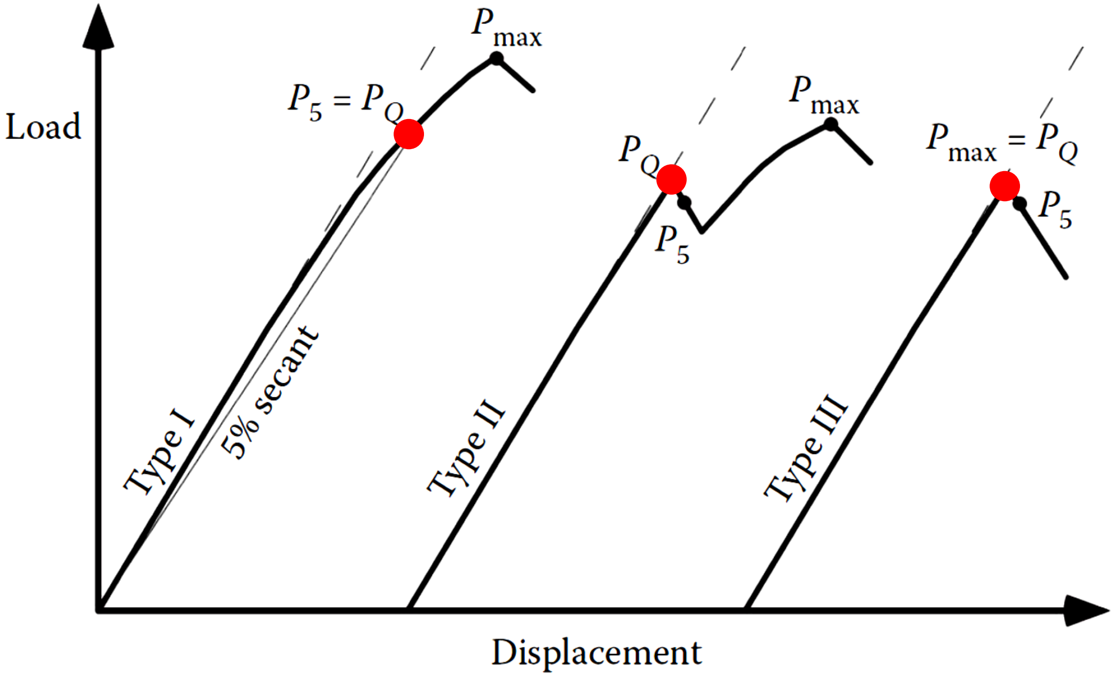
$P_{max} / P_Q < 1.1$ ➡ Calculus of K_Q

$P_{max} / P_Q > 1.1$ ➡ Test invalid

K_{Ic} Testing

Three types of load–displacement behavior in a K_{Ic} test

- When a precracked test specimen is loaded to failure, load and displacement are monitored. Three types of load–displacement curves are shown in following figure.



K_{Ic} Testing

Calculation of the *trial* value K_Q with the relation :

$$K_Q = \frac{P_Q}{BW^{1/2}} f\left(\frac{a}{W}\right)$$

If moreover,

$$B,\ a,\ W-a \geq 2.5\left(\frac{K_Q}{\sigma_Y}\right)^2$$ ✓

$$0.45 \leq a/W \leq 0.55$$ ✓

$$P_{max} \leq 1.1 P_Q$$ ✓

then K_Q is equal to K_{IC}

When the test result fails to meet these requirements, use a 1.5 times larger specimen.

K_{Ic} Testing

Example 1:

- Consider a structural steel with σ_{YS} = 350 MPa. Estimate the specimen dimensions required for a valid K_{Ic} test. Assume that this material is on the upper shelf of toughness, where typical K_{Ic} values for initiation of microvoid coalescence in these materials are around 200 MPam$^{0.5}$.

Solution:

$$W - a = 2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2 = 2.5\left(\frac{200\,MPa\sqrt{m}}{350\,MPa}\right)^2 = 0.816\ m$$

- Since a/W= 0.5, W = 1.63 m. If W/B = 4, then the required specimen thickness is 408 mm. If the specimen were side grooved, the specimen thickness could be reduced and plane strain conditions were maintained at the crack tip. Nevertheless, a very large specimen would be required for a valid K_{Ic} test in this material.

K_{Ic} Testing

Example 2:

- Given the material in Example 7.1 (σ_{YS} = 350 MPa), estimate the largest valid K_{Ic} that can be measured when W − a = 10 mm, 25 mm, and 50 mm.

Solution:

$$K_{Ic} = \sigma_{YS} \sqrt{\frac{W - a}{2.5}}$$

$$K_{Ic} = 350\,MPa \sqrt{\frac{0.010\,m}{2.5}} = 22.1\,MPa\sqrt{m}$$

$$K_{Ic} = 350\,MPa \sqrt{\frac{0.025\,m}{2.5}} = 35\,MPa\sqrt{m}$$

$$K_{Ic} = 350\,MPa \sqrt{\frac{0.050\,m}{2.5}} = 49.5\,MPa\sqrt{m}$$