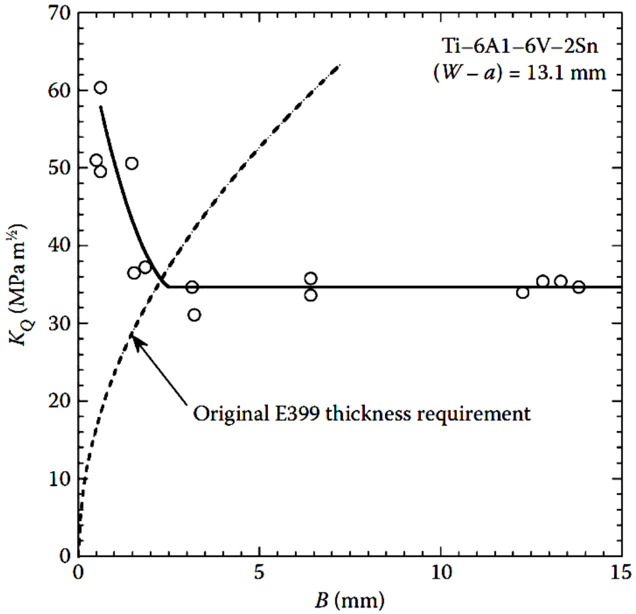
دانشگاه صنعتی اصفهان
دانشکده مکانیک

Fracture Toughness Testing (2)

Limitations of E399 and Similar Standards

- The 1960s-vintage data that led to the hypothesis of a transition from “plane stress fracture” to “plane strain fracture” consisted almost entirely of materials that fail by microvoid coalescence.
- The observed thickness effect on fracture toughness is due to a competition between two fracture morphologies: slant fracture, which occurs on a 45° plane, and flat fracture, where the fracture plane is normal to the applied stress.

In thinner specimens, the apparent fracture toughness is higher because slant fracture dominates.

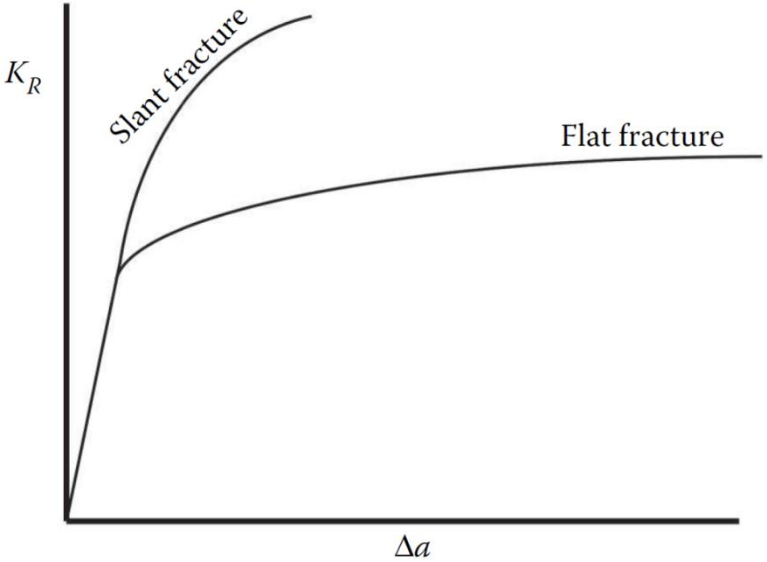


Effect of specimen thickness on apparent fracture toughness in a titanium alloy.

Limitations of E399 and Similar Standards

- When crack extension occurs by ductile tearing (microvoid coalescence), fracture toughness is characterized by a rising R curve. As the following figure illustrates, the R curve for slant fracture is significantly steeper than for flat fracture. The effective R curve for a specimen that experiences both morphologies will fall somewhere between these extremes.

The relative amount of slant versus flat fracture affects the K_Q value, as measured in accordance with the E399 procedure. A side-grooved specimen eliminates the shear lips and enables the R curve for at fracture to be determined. ASTM E399 has recently been revised to allow side grooves.



Effect of fracture morphology on the resistance to ductile tearing. Slant fracture results in a steeper R curve than flat fracture.

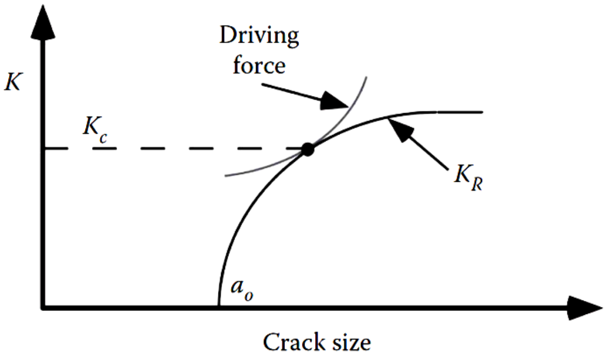
Limitations of E399 and Similar Standards

- In the E399 set a maximum of 1.10 on the P_{max}/P_Q ratio, this additional restriction has been somewhat effective in reducing the size effect because it excludes materials with a steep R curve.

K–R Curve Testing

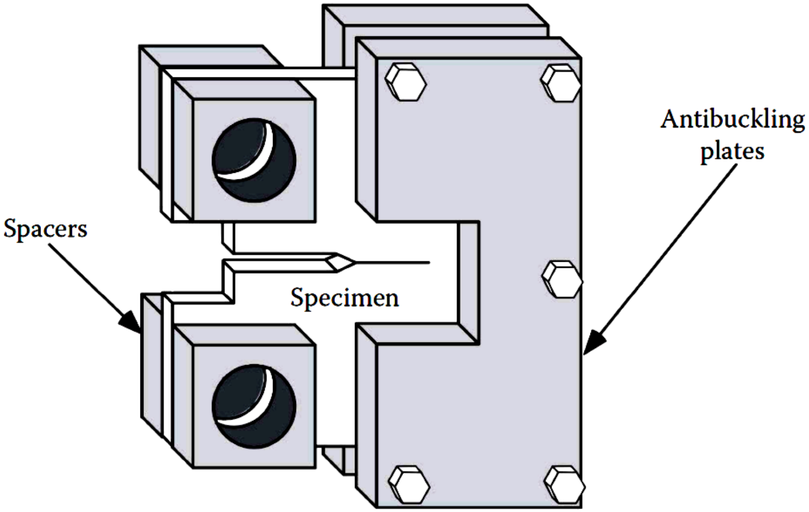
- The materials that fail by microvoid coalescence usually exhibit a rising R curve. The ASTM E399 test method measures a single point on the R curve. This method contains an inherent size dependence on apparent toughness because the point on the R curve at which K_Q is defined is a function of ligament length.
- The *ASTM Standard E561* outlines a procedure for determining K versus crack growth curves in such materials. Unlike the original ASTM E399 test method, the K–R standard does not contain a minimum thickness requirement, and thus can be applied to thin sheets. The figure illustrates a typical K–R curve in a predominantly linear elastic material.

The R curve is initially very steep, as little or no crack growth occurs with increasing K_I. As the crack begins to grow, K increases with crack growth until a steady state is reached, where the R curve becomes flat. It is possible to define a critical stress intensity, K_c, where the driving force is tangent to the R curve.



K–R Curve Testing

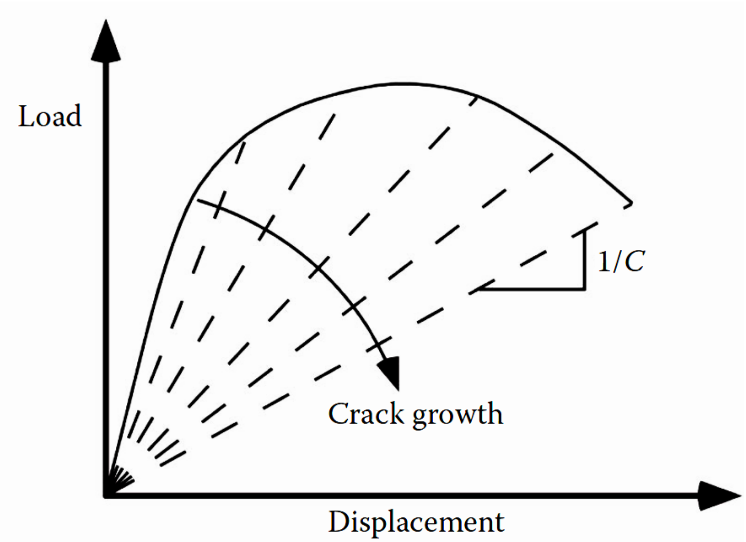
- The ASTM standard E561 for K–R curve testing permits three configurations of test specimen: the MT geometry, the conventional C(T) specimen, and a wedge-loaded compact specimen. Since this test method is often applied to thin sheets, specimens do not usually have the conventional geometry, with the width being equal to twice the thickness. The specimen thickness is normally fixed by the sheet thickness, and the width is governed by the anticipated toughness of the material, as well as the available test fixtures.
- One problem with thin-sheet fracture toughness testing is that the specimens are subject to out-of-plane buckling, which leads to combined Mode I–Mode III loading of the crack. Consequently, an antibuckling device should be fitted to the specimen.



K–R Curve Testing

Experimental Measurement of K–R Curves

- The ASTM Standard E561 outlines a number of alternative methods for computing both K_I and the crack extension in an R curve test; the most appropriate approach depends on the relative size of the plastic zone.
  - For negligible plasticity
- As the crack grows, the load–displacement curve deviates from its initial linear shape because the compliance continuously changes. If the specimen were unloaded prior to fracture, the curve would return to the origin, as the dashed lines indicate.

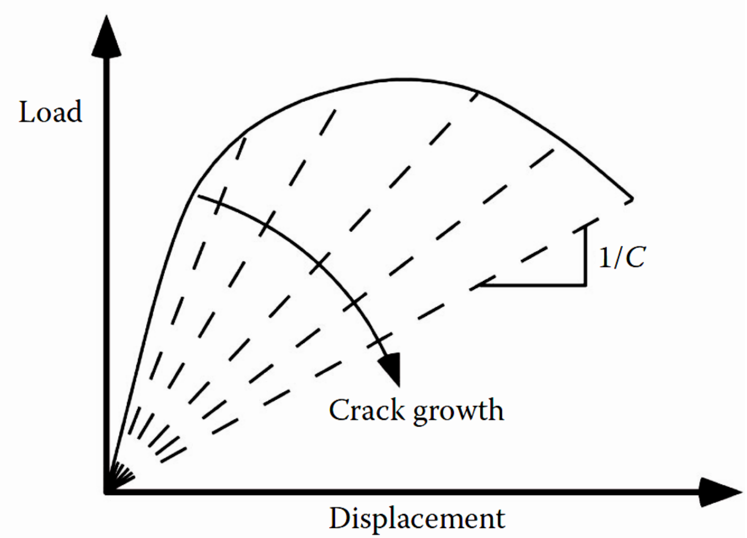


K–R Curve Testing

Experimental Measurement of K–R Curves

- For negligible plasticity

- The compliance at any point during the test is equal to the displacement divided by the load. The instantaneous crack length can be inferred from the compliance through relationships that are given in the ASTM standard.



From ASTM Standard E561 “Crack Length-Compliance Relationships for Compact”

$$\frac{a}{W} = 1.00196 - 4.06319U_{LL} + 11.242U_{LL}^2 - 106.043U_{LL}^3 + 464.335U_{LL}^4 - 650.677U_{LL}^5$$

where: $$U_{LL} = \frac{1}{\sqrt{\frac{BE\Delta}{P}} + 1}$$

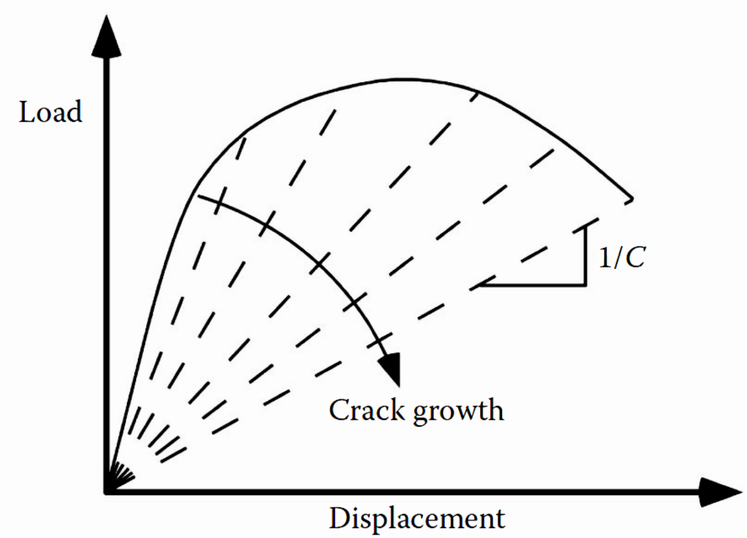
K–R Curve Testing

Experimental Measurement of K–R Curves

- For negligible plasticity

- The instantaneous stress intensity is related to the current values of load and crack length:

$$K_I = \frac{P}{B\sqrt{W}} f\,(a/W)$$

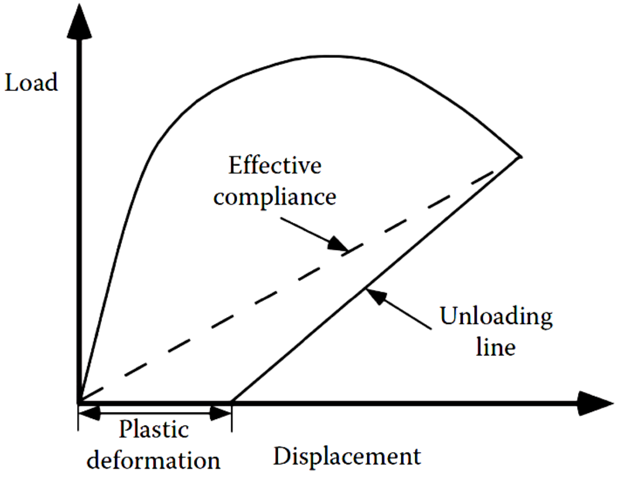


K–R Curve Testing

Experimental Measurement of K–R Curves

- For plastic zone forms ahead of the growing crack

- The nonlinearity in the load–displacement curve is caused by a combination of crack growth and plasticity, as the figure illustrates. If the specimen is unloaded prior to fracture, the load–displacement curve does not return to the origin; crack tip plasticity produces a finite amount of permanent deformation in the specimen. The physical crack length can be determined optically or from unloading compliance, where the specimen is partially unloaded, the elastic compliance is measured, and the crack length is inferred from compliance. The stress intensity should be corrected for plasticity effects by determining an effective crack length.



K–R Curve Testing

Experimental Measurement of K–R Curves

- For plastic zone forms ahead of the growing crack

- The ASTM standard suggests two alternative approaches for computing a_{eff}: the *Irwin plastic zone* correction and the *secant method*.

Irwin plastic zone :

$$a_{eff} = a + \frac{1}{2\pi}\left(\frac{K}{\sigma_{YS}}\right)^2$$

secant method: determining an effective crack size from the effective compliance, which is equal to the total displacement divided by the load (pervious figure)

- for both methods is computed from the load and the effective crack length:

$$K_{eff} = \frac{P}{B\sqrt{W}} f\left(\frac{a_{eff}}{W}\right)$$

K–R Curve Testing

- The ASTM K–R curve standard requires that the stress intensity be plotted against effective crack extension (Δa_{eff}). This practice is inconsistent with the J_{Ic} and J–R curve approaches, where J is plotted against physical crack extension. The estimate of the instability point (Kc) should not be sensitive to the way in which crack growth is quantified, particularly when both the driving force and resistance curves are computed with a consistent definition of Δa.

- The ASTM E561 standard does not contain requirements on specimen size or the maximum allowable crack extension; thus there is no guarantee that a K–R curve produced according to this standard will be a geometry-independent material property. The inplane dimensions must be large compared with the plastic zone in order for LEFM to be valid.
- Application of the secant approach reduces but does not eliminate the size dependence.