دانشگاه صنعتی اصفهان

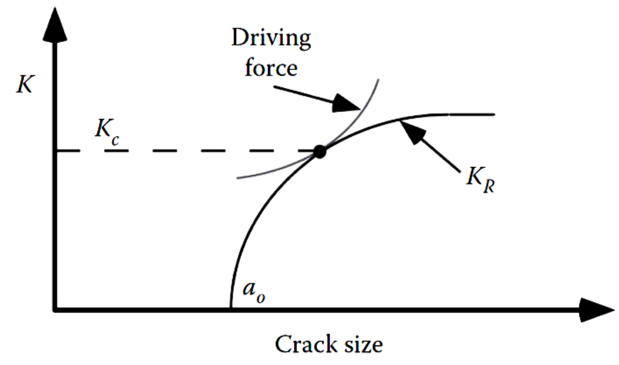
دانشکده مکانیک

Fracture Toughness Testing (3)

K–R Curve Testing

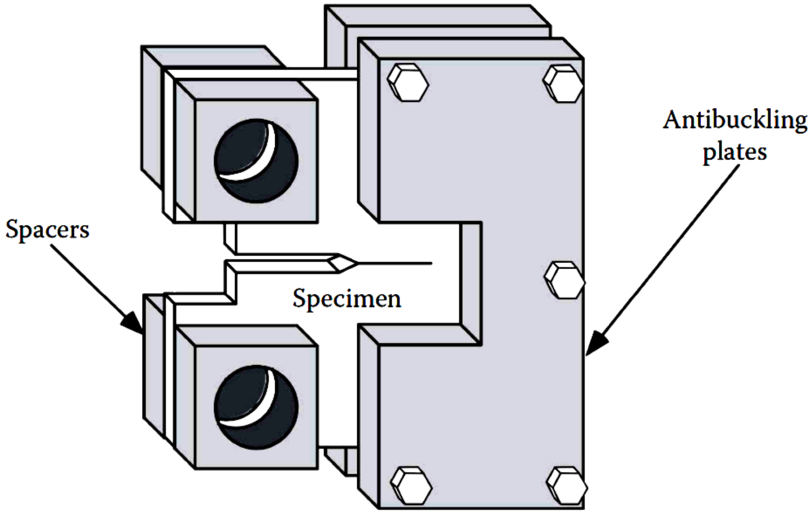
- The materials that fail by microvoid coalescence usually exhibit a rising R curve. The ASTM E399 test method measures a single point on the R curve. This method contains an inherent size dependence on apparent toughness because the point on the R curve at which K_Q is defined is a function of ligament 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.



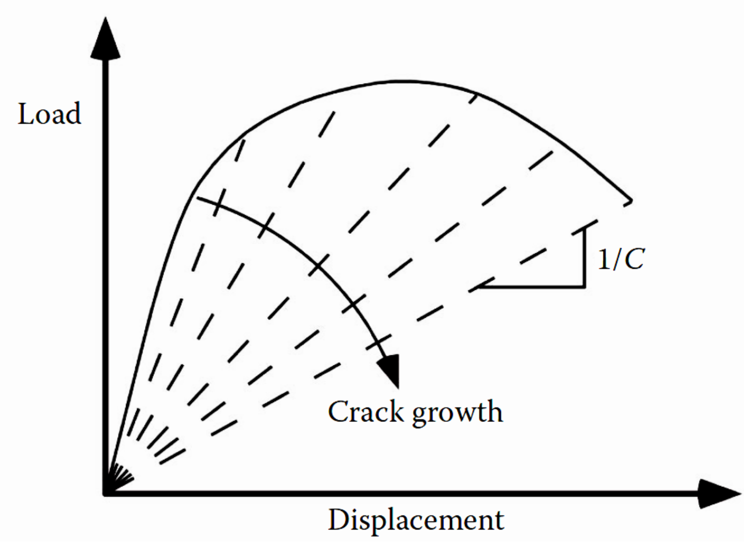
K–R Curve Testing

- 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.



Experimental Measurement of K–R Curves

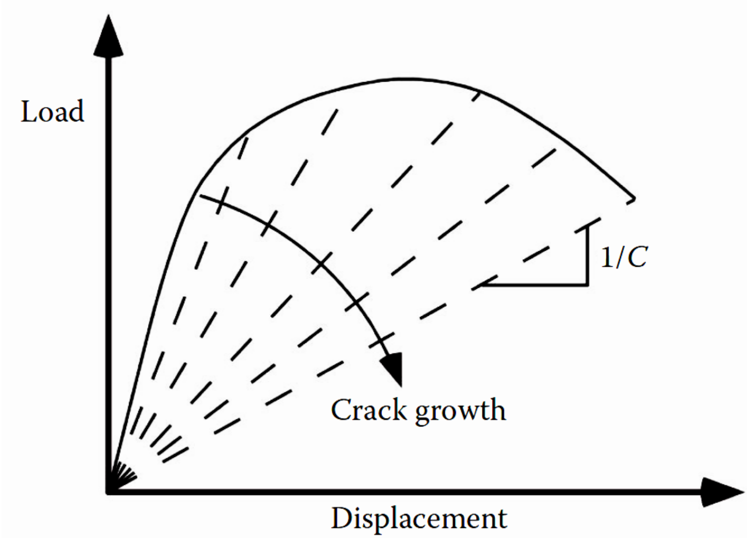
- The ASTM Standard E561 outlines a number of alternative methods for computing both K_I and the crack extension in an R curve test; the most appropriate approach depends on the relative size of the plastic zone.
  - For negligible plasticity
- As the crack grows, the load–displacement curve deviates 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.



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"

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

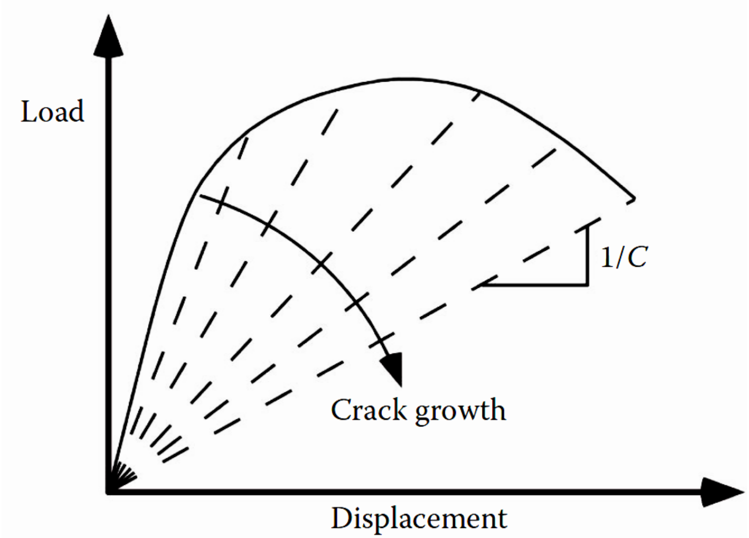
where: $$U_{LL} = \frac{1}{\sqrt{\frac{BE\Delta}{P}} + 1}$$

Experimental Measurement of K–R Curves

- For negligible plasticity

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

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

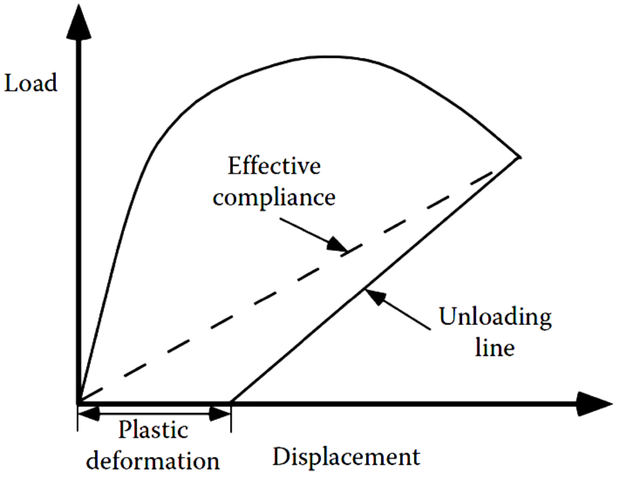


K–R Curve Testing

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.



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.

J Testing of Metals

- The *ASTM E1820* has two alternative methods for J tests: the basic procedure and the resistance curve procedure. The basic procedure entails monotonically loading the specimen to failure (measure J at fracture instability, J_{IC}) or to a particular displacement, depending on the material behavior. The resistance curve procedure requires that crack growth be monitored during the test. The J integral is calculated incrementally in the resistance curve procedure.

- Measuring toughness near the onset of ductile crack extension, J_{Ic}, requires the determination of a J resistance curve. If the basic procedure is used to generate such a resistance curve, the J values on the R curve may be subject to error because they have not been corrected for crack growth. This is of little consequence when measuring J_{Ic}, however, because the purpose of the R curve in this instance is to extrapolate back to a J value where Δa is small and a crack growth correction is not necessary.

The Basic Test Procedure and J_{Ic} Measurements

- As crack growth is not monitored as part of the basic test procedure, a multiple-specimen technique is normally required to obtain a J–R curve. In such cases, a series of nominally identical specimens are loaded to various levels and then unloaded. Different amounts of crack growth occur in the various specimens. The crack growth in each sample is marked by heat tinting or fatigue cracking after the test. Each specimen is then broken open and the crack extension is measured.
- In addition to measuring crack growth, a J value must be computed for each specimen in order to generate the R curve. For estimation purposes, it is convenient to divide J into elastic and plastic components: $J = J_{el} + J_{pl}$

$$J_{el} = \frac{K_I^{\,2}(1-\nu^2)}{E} \quad \text{with:} \quad K_I = \frac{P}{B\sqrt{W}} f\,(a/W)$$

$$f\,(a/W) = \frac{[(2+a/w)(0.886+4.64(a/w)-13.32(a/w)^2+14.72(a/w)^3-5.6(a/w)^4]}{(1-a/w)^{3/2}}$$

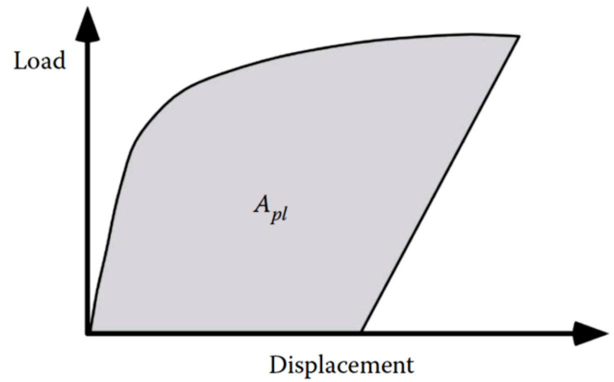
The Basic Test Procedure and J_{Ic} Measurements

- From ASTM E1820 (from the energy release rate definition of J): $J_{pl} = \dfrac{\eta A_{pl}}{B_N b_0}$

For an SE(B) specimen: $\eta = 2$

For a C(T) specimen: $\eta = 2 + 0.522 b_0 / W$

A_{pl} is the plastic area under the load–displacement curve:



B is the net thickness and b_o is the initial ligament length.

The Basic Test Procedure and J_{Ic} Measurements

- The resistance curve procedure described in which J is computed incrementally with updated values of crack length and ligament length, can also be applied. This more elaborate procedure is usually not necessary for J_{Ic} measurements, however, because crack growth is insignificant at the point on the R curve where J_{Ic} is measured. In the limit of a stationary crack, both formulas give identical results.

- The ASTM procedure for computing J_Q, a provisional J_{Ic}, from the R curve is illustrated in following figure. Exclusion lines are drawn at crack extension (Δa) values of 0.15 and 1.5 mm. The slope of the exclusion lines is intended to represent the component of crack extension that is due to crack blunting, as opposed to ductile tearing. A horizontal exclusion line is defined at a limiting value of *J*:

$$J_{\lim it} = \frac{b_0 \sigma_Y}{7.5}$$

The Basic Test Procedure and J_{Ic} Measurements

- All data that fall within the exclusion limits are fit to a power-law expression:

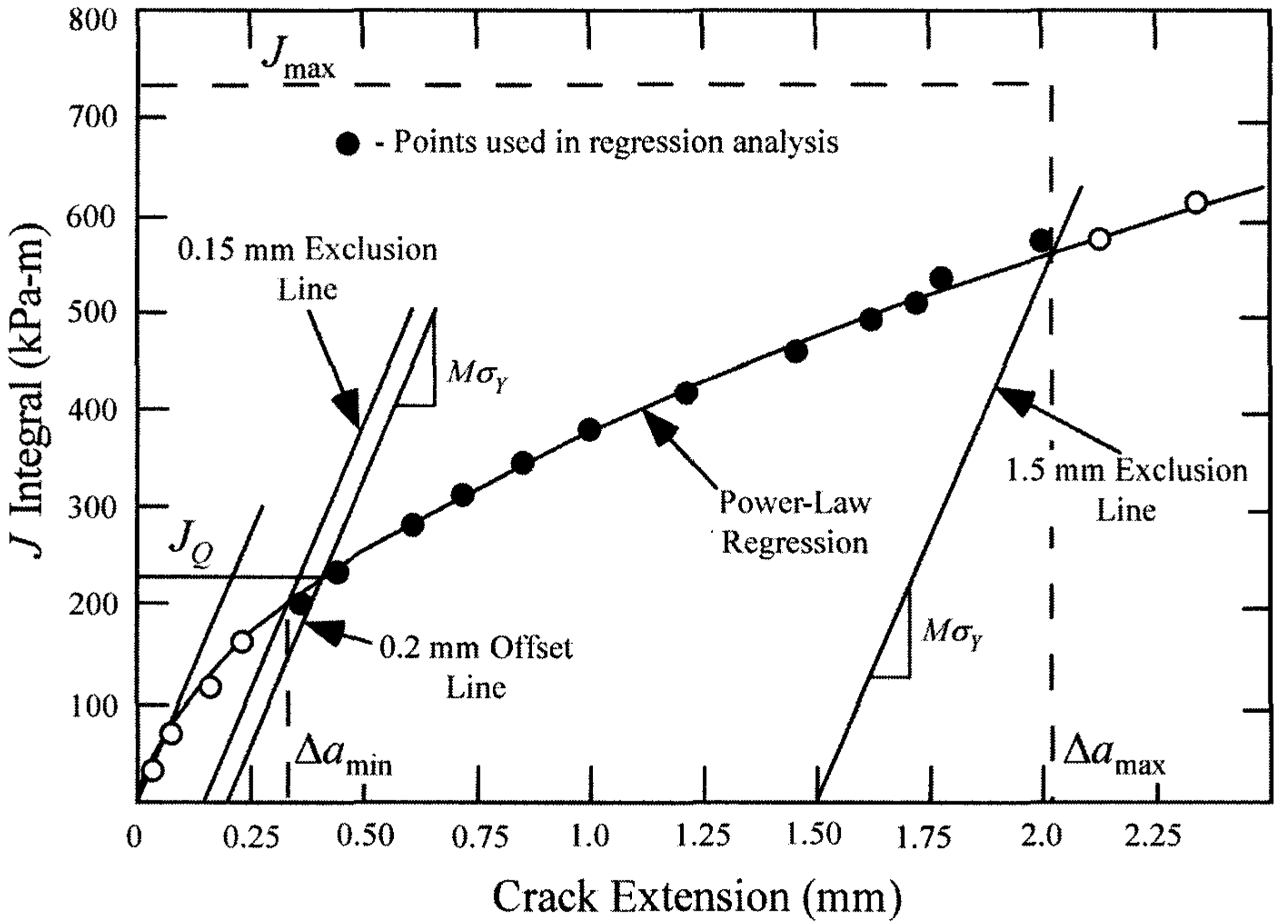
$$J = C_1 (\Delta a)^{C_2}$$

- The J_Q value is defined as the intersection between above equation and a 0.2 mm offset line. If all other validity criteria are met, $J_Q = J_{Ic}$ as long as the following size requirements are satisfied:

$$B, b_0 \geq \frac{10 J_Q}{\sigma_Y} \qquad (*)$$

The Basic Test Procedure and J_{Ic} Measurements

Determination of J_Q from ASTM E 1820:



Exampl:

- Estimate the specimen size requirements for a valid J_{Ic} test on the material in pervious example. Assume σ_{TS} = 450 MPa and E = 207,000 MPa.

Solution:

First we must convert the K_{Ic} value in pervious example into an equivalent J_{Ic}:

$$J_{Ic} = \frac{K_{IC}^2(1-\nu^2)}{E} = \frac{(200\,MPa\sqrt{m}\;)^2(1-0.3^2)}{207000\,MPa} = 0.176\;MPa\,m$$

Substituting the above result into Equation (*) gives:

$$B, b_0 \geq = \frac{(25)(0.176\,MPa\,m\;)}{400\,MPa} = 4.4\;mm$$

which is more than two orders of magnitude lower than the specimen dimension that ASTM E399 requires for this material. Thus, the J_{Ic} size requirements are much more lenient than the K_{Ic} requirements.