

tacular, reaching velocities as high as 1 mile/sec!^[14] The structure effectively “unzips.”* The factor of safety for fracture-mechanics failure is defined as

$$N_{FM} = \frac{K_C}{K} \quad (5.15)$$

Note that this can be a moving target if cracks are in a growth mode because K is a function of crack width. If the current, or typical, crack width is known for the part and the fracture toughness K_C is known for the material, then the maximum allowable nominal stress can be determined for any chosen safety factor or vice versa. The allowable stress for any chosen safety factor calculated from the appropriate version of equation 5.14c will typically be lower than that calculated based on yield strength using equations 5.8 (pp. 260–262) or 5.11 (p. 265). The effect of time-varying (dynamic) stresses on the stress intensity factor K and on failure will be addressed in the next chapter.

To determine the fracture toughness, K_C , ASTM-standardized specimens,[†] containing a crack of defined dimensions, are tested to failure. For axial tests, the specimen is gripped in a servo-hydraulic testing machine such that it can be tensioned across the crack. (Bending tests place the crack on the tension side of the beam.) The specimen is loaded dynamically with increasing displacements and its load-displacement characteristic (effective spring rate) is monitored. The load-displacement function becomes nonlinear at the start of rapid crack growth. The fracture toughness K_C is measured at this point.

Fracture toughness K_C for engineering metals ranges from 20 to 200 MPa-m^{0.5}; engineering polymers' and ceramics' K_C ranges from 1 to 5 MPa-m^{0.5}.^[15] *Fracture toughness generally parallels ductility and increases substantially at high temperatures.* Higher-strength steels tend to be less ductile and have lower K_C than lower-strength steels. Substitution of a high-strength steel for a low-strength steel has led to failures in some applications due to the reduction in fracture toughness that accompanied the material change.

Another example of a fracture-mechanics failure is shown in Figure 5-20a, which is a photograph of the low-carbon-steel trailer hitch ball bracket of Figures 1-2 through 1-6 (pp. 14–16). This part failed suddenly while being bent to shape at a red heat. The fracture surface can be seen to be relatively smooth, and the edges of the crack are extremely sharp. Since elevated temperature increases both ductility and fracture toughness, a sudden brittle failure is unusual under these circumstances. A closer inspection of the failure surface (shown at 12.5X magnification in Figure 5-20b) shows a small crack that was apparently a flaw in the hot-rolled bar of steel. The stress intensity at this crack tip exceeded the fracture toughness of the material at its elevated temperature and a sudden brittle failure resulted.[‡]

This brief discussion of fracture mechanics has barely *scratched the surface* of this complex topic. The reader is encouraged to read further on this subject. Sources for general information on fracture mechanics, stress intensity factors, and fracture-toughness properties of materials are noted in the bibliography of this chapter.

* On the occasion of the 75th anniversary of the Boston molasses tank rupture described earlier, a 91-year-old Boston resident was interviewed and described what he saw and heard as a 16-year-old boy in January 1919 when he witnessed the tank failure from atop Cobb's Hill in Boston's North End. He recalled a sudden popping sound, like machine-gun fire, followed quickly by a loud explosion. The “machine-gun sound” was quite likely the sound of the crack propagating across the tank wall at up to 1 mile/second and the loud explosion was probably that of the molasses pressure bursting and disintegrating the tank, large pieces of which landed on and destroyed houses hundreds of yards away.

† See ASTM E-399-83 “Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials.”

‡ Note that LEFM cannot be used to analyze this failure because it was not in the linear elastic range. The entire cross section was being plastically deformed at the time of failure. A nonlinear fracture-mechanics analysis would be needed here.