Back to basics – Fracture toughness testing

Understanding the underlying theory behind fracture toughness testing, and how the test is conducted.

In previous articles, we have discussed the many different types of mechanical testing methods and requirements. While some of the test methods have application to the design process (tensile testing), many of the methods are not related to the design of the part. In this article, we will discuss fracture mechanics and fracture toughness testing. These methods are directly applicable to design, as well as can establish non-destructive testing (NDT) criteria for in-use parts. This method is powerful, and is used predominantly in aerospace, but is finding more applications in automotive and other fields.

FRACTURE MECHANICS

In 1920, Griffith [1] proposed the concept that all materials contained flaws. It is these flaws that result in materials that have substantially lower strength than their theoretical maximum. These small flaws in the material reduce the fracture strength of the material by stress concentrations [2]. These stress concentrations cause the theoretical cohesive strength to be achieved in local regions. Griffith created the criterion that “a crack will propagate when the decrease in strain energy is at least equal to the energy required to create a new crack surface [3].” This criterion is used to establish when a flaw of a specific size will initiate cracking and propagate in a brittle manner.

Metals that fail in a brittle fashion will experience plastic deformation before failure [4] [5]. Because of the plastic deformation prior to brittle fracture, the Griffith Microcrack Theory does not apply to metals. However, Irwin [6] proposed that the stress at the crack tip was a function of the applied stress and the crack size:

$$ K = \sigma \sqrt{\pi c} $$

where $K$ is the stress intensity factor and $c$ is the half-length of a flaw. $K$ is completely defined by the crack geometry, applied stress, and specimen geometry. The value of the stress intensity factor when unstable crack growth occurs is the critical stress intensity factor, $K_c$ (for mode I – cracking opening under tensile forces), where the value of $K_c$ is a material property. While the above is for an elliptical flaw, other flaw shapes have also been calculated [7] [8]. This assumes that plane strain conditions have been realized. If plane stress conditions are present, then the stress is relaxed by the increased plastic zone at the crack tip. Further, the state of stress is no longer triaxial and is diminished.

Toughness is a measure of the energy required to resist fracture in a material. Often this property is more important than the actual tensile properties, particularly if the part is to be used in a dynamic environment. The term impact strength is used to denote the toughness of the material. This term is a misnomer; it should really be impact energy. However, impact strength is so established that it makes little sense to change it. Toughness is strongly dependent on the rate of loading, temperature, and the presence of stress concentrations. Several standardized tests have been developed since World War II to measure the resistance to brittle fracture, notably the Charpy V-Notch test [9] discussed in the previous article. These tests are attempts to quantify the behavior of the material in service.

FRACTURE TOUGHNESS TESTING

As indicated earlier, the use of fracture mechanics is important in determining the maximum flaw size that a material can withstand before failing catastrophically. As has been noted, cracking in a thick plate is worse than in a thin plate. This is because...
of plane strain conditions. At the crack tip, the plastic zone is small, with a high-stress gradient across the plastic zone (Figure 1). High tri-axial stresses are present at the crack tip. The fracture appearance changes with specimen thickness because of the amount of triaxial stresses. (Figure 2).

In thin plates, the fracture is characterized by a mixed mode ductile and brittle fracture, with the presence of shear lips. Under plane strain conditions, when the plate is thick enough the fracture is flat, and the fracture stress is a constant with increasing thickness. The minimum thickness for plane strain conditions to occur is given by:

$$B = 2.5 \left( \frac{K_{Ic}}{\sigma_{ys}} \right)^2$$

Different configurations of test specimens are used to determine the plane-strain fracture toughness, $K_{Ic}$ [11]. Typical specimens are shown in Figure 3. For most applications, the compact specimen is used because less material is used.

The notch is machined in the specimen and made sharper by fatiguing at low cycle, high strain until the crack is about the width of the test specimen. The initial crack length is measured by including the length of the fatigue crack and the notch. Testing of the specimen is accomplished by loading the specimen in tension, with the load and crack opening displacement continuously recorded until failure. A conditional value of fracture toughness, $K_Q$ is calculated. The methodology of calculating $K_Q$ is dependent on the type of specimen used. Refer to ASTM E399 for details.

To determine the fracture toughness, $K_{Ic}$, the crack length, $a$, is measured, and $B$ is calculated:

$$B = 2.5 \left( \frac{K_{Ic}}{\sigma_{ys}} \right)^2$$

If both $B$ and $a$ are less than the width $b$ of the specimen, then $K_Q = K_{Ic}$. If not, then a thicker specimen is required, and $K_Q$ is used to determine the new thickness. Typical $K_{Ic}$ values for steels are shown in Table 1.

**CONCLUSIONS**

In this short article, we have described the underlying theory behind fracture toughness testing, and how the test is conducted. In the next set of articles, we will describe fatigue and how fracture toughness testing can be used to calculate fatigue life.

Should there be any questions regarding this article, or suggestions for future articles, please contact the editor or myself.

**REFERENCES**


