The ability of a metal

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The ability of a metal to deform plastically and to absorb energy in the process before fracture is termed toughness. The emphasis of this definition should be placed on the ability to absorb energy before fracture. Recall that ductility is a measure of how much something deforms plastically before fracture, but just because a material is ductile does not make it tough. The key to toughness is a good combination of strength and ductility. A material with high strength and high ductility will have more toughness than a material with low strength and high ductility. Therefore, one way to measure toughness is by calculating the area under the stress strain curve from a tensile test. This value is simply called “ material toughness” and it has units of energy per volume. Material toughness equates to a slow absorption of energy by the material.

There are several variables that have a profound influence on the toughness of a material. These variables are:

- train rate (rate of loading).
- Temperature.
- Notch effect.

A metal may possess satisfactory toughness under static loads but may fail under dynamic loads or impact. As a rule ductility and, therefore, toughness decrease as the rate of loading increases. Temperature is the second variable to have a major influence on its toughness. As temperature is lowered, the ductility and toughness also decrease. The third variable is termed notch effect, has to due with the distribution of stress. A material might display good toughness when the applied stress is uniaxial; but when a multiaxial stress state is produced due to the presence of a notch, the material might not withstand the simultaneous elastic and plastic deformation in the various directions.

There are several standard types of toughness test that generate data for specific loading conditions and/or component design approaches. Three of the toughness properties that will be discussed in more detail are:

1. Impact toughness.
2. Notch toughness.
3. Fracture toughness.

Impact Toughness:

The impact toughness (AKA Impact strength) of a material can be determined with a Charpy or Izod test. These tests are named after their inventors and were developed in the early 1900's before fracture mechanics theory was available. Impact properties are not directly used in fracture mechanics calculations, but the economical impact tests continue to be used as a quality control method to assess notch sensitivity and for comparing the relative toughness of engineering materials.

The two tests use different specimens and methods of holding the specimens, but both tests make use of a pendulum-testing machine. For both tests, the specimen is broken by a single overload event due to the impact of the pendulum. A stop pointer is used to record how far the pendulum swings back up after fracturing the specimen. The impact toughness of a metal is determined by measuring the energy absorbed in the fracture of the specimen. This is simply obtained by noting the height at which the pendulum is released and the height to which the pendulum swings after it has struck the specimen . The height of the pendulum times the weight of the pendulum produces the potential energy and the difference in potential energy of the pendulum at the start and the end of the test is equal to the absorbed energy.

Since toughness is greatly affected by temperature, a Charpy or Izod test is often repeated numerous times with each specimen tested at a different temperature. This produces a graph of impact toughness for the material as a function of temperature. An impact toughness versus temperature graph for a steel is shown in the image. It can be seen that at low temperatures the material is more brittle and impact toughness is low. At high temperatures the material is more ductile and impact toughness is higher. The transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of a material.

Fracture Toughness:

Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. It is a very important material property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture.

A parameter called the stress-intensity factor (K) is used to determine the fracture toughness of most materials. A Roman numeral subscript indicates the mode of fracture and the three modes of fracture are illustrated in the image to the right. Mode I fracture is the condition in which the crack plane is normal to the direction of largest tensile loading. This is the most commonly encountered mode and, therefore, for the remainder of the material we will consider KI.

The stress intensity factor is a function of loading, crack size, and structural geometry. The stress intensity factor may be represented.

Role of Material Thickness:

Specimens having standard proportions but different absolute size produce different values for KI. This results because the stress states adjacent to the flaw changes with the specimen thickness (B) until the thickness exceeds some critical dimension. Once the thickness exceeds the critical dimension, the value of KI becomes relatively constant and this value, KIC , is a true material property which is called the plane-strain fracture toughness. The relationship between stress intensity, KI, and fracture toughness, KIC, is similar to the relationship between stress and tensile stress. The stress intensity, KI, represents the level of “ stress” at the tip of the crack and the fracture toughness, KIC, is the highest value of stress intensity that a material under very specific (plane-strain) conditions that a material can withstand without fracture. As the stress intensity factor reaches the KIC value, unstable fracture occurs. As with a material’s other mechanical properties, KIC is commonly reported in reference books and other sources.

Plane Strain:

A condition of a body in which the displacements of all points in the body are parallel to a given plane, and the values of theses displacements do not depend on the distance perpendicular to the plane.

Plane Stress:

A condition of a body in which the state of stress is such that two of the principal stresses are always parallel to a given plane and are constant in the normal direction.

Plane-Strain and Plane-Stress:

When a material with a crack is loaded in tension, the materials develop plastic strains as the yield stress is exceeded in the region near the crack tip. Material within the crack tip stress field, situated close to a free surface, can deform laterally (in the z-direction of the image) because there can be no stresses normal to the free surface. The state of stress tends to biaxial and the material fractures in a characteristic ductile manner, with a 45o shear lip being formed at each free surface. This condition is called “ plane-stress” and it occurs in relatively thin bodies where the stress through the thickness cannot vary appreciably due to the thin section.

However, material away from the free surfaces of a relatively thick component is not free to deform laterally as it is constrained by the surrounding material. The stress state under these conditions tends to triaxial and there is zero strain perpendicular to both the stress axis and the direction of crack propagation when a material is loaded in tension. This condition is called “ plane-strain” and is found in thick plates. Under plane-strain conditions, materials behave essentially elastic until the fracture stress is reached and then rapid fracture occurs. Since little or no plastic deformation is noted, this mode fracture is termed brittle fracture.

Plane-Strain Fracture Toughness Testing:

When performing a fracture toughness test, the most common test specimen configurations are the single edge notch bend (SENB or three-point bend), and the compact tension (CT) specimens. From the above discussion, it is clear that an accurate determination of the plane-strain fracture toughness requires a specimen whose thickness exceeds some critical thickness (B). Testing has shown that plane-strain conditions generally prevail when:

When a material of unknown fracture toughness is tested, a specimen of full material section thickness is tested or the specimen is sized based on a prediction of the fracture toughness. If the fracture toughness value resulting from the test does not satisfy the requirement of the above equation, the test must be repeated using a thicker specimen. In addition to this thickness calculation, test specifications have several other requirements that must be met (such as the size of the shear lips) before a test can be said to have resulted in a KIC value.

When a test fails to meet the thickness and other test requirement that are in place to insure plane-strain condition, the fracture toughness values produced is given the designation KC. Sometimes it is not possible to produce a specimen that meets the thickness requirement. For example when a relatively thin plate product with high toughness is being tested, it might not be possible to produce a thicker specimen with plain-strain conditions at the crack tip.

Plane-Stress and Transitional-Stress States:

For cases where the plastic energy at the crack tip is not negligible, other fracture mechanics parameters, such as the J integral or R-curve, can be used to characterize a material. The toughness data produced by these other tests will be dependant on the thickness of the product tested and will not be a true material property. However, plane-strain conditions do not exist in all structural configurations and using KIC values in the design of relatively thin areas may result in excess conservatism and a weight or cost penalty. In cases where the actual stress state is plane-stress or, more generally, some intermediate- or transitional-stress state, it is more appropriate to use J integral or R-curve data, which account for slow, stable fracture (ductile tearing) rather than rapid (brittle) fracture.

Uses of Plane-Strain Fracture Toughness:

KIC values are used to determine the critical crack length when a given stress is applied to a component.

Orientation:

The fracture toughness of a material commonly varies with grain direction. Therefore, it is customary to specify specimen and crack orientations by an ordered pair of grain direction symbols. The first letter designates the grain direction normal to the crack plane. The second letter designates the grain direction parallel to the fracture plane. For flat sections of various products, e. g., plate, extrusions, forgings, etc., in which the three grain directions are designated (L) longitudinal, (T) transverse, and (S) short transverse, the six principal fracture path directions are: L-T, L-S, T-L, T-S, S-L and S-T.

Fatigue Properties:

Fatigue cracking is one of the primary damage mechanisms of structural components. Fatigue cracking results from cyclic stresses that are below the ultimate tensile stress, or even the yield stress of the material. The name " fatigue" is based on the concept that a material becomes " tired" and fails at a stress level below the nominal strength of the material. The facts that the original bulk design strengths are not exceeded and the only warning sign of an impending fracture is an often hard to see crack, makes fatigue damage especially dangerous.

The fatigue life of a component can be expressed as the number of loading cycles required to initiate a fatigue crack and to propagate the crack to critical size. Therefore, it can be said that fatigue failure occurs in three stages – crack initiation; slow, stable crack growth; and rapid fracture.

As discussed previously, dislocations play a major role in the fatigue crack initiation phase. In the first stage, dislocations accumulate near surface stress concentrations and form structures called persistent slip bands (PSB) after a large number of loading cycles. PSBs are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes. This leaves tiny steps in the surface that serve as stress risers where tiny cracks can initiate. These tiny crack (called microcracks) nucleate along planes of high shear stress which is often 45o to the loading direction.

In the second stage of fatigue, some of the tiny microcracks join together and begin to propagate through the material in a direction that is perpendicular to the maximum tensile stress. Eventually, the growth of one or a few crack of the larger cracks will dominate over the rest of the cracks. With continued cyclic loading, the growth of the dominate crack or cracks will continue until the remaining uncracked section of the component can no longer support the load. At this point, the fracture toughness is exceeded and the remaining cross-section of the material experiences rapid fracture. This rapid overload fracture is the third stage of fatigue failure.

Factors Affecting Fatigue Life

In order for fatigue cracks to initiate, three basic factors are necessary. First, the loading pattern must contain minimum and maximum peak values with large enough variation or fluctuation. The peak values may be in tension or compression and may change over time but the reverse loading cycle must be sufficiently great for fatigue crack initiation. Secondly, the peak stress levels must be of sufficiently high value. If the peak stresses are too low, no crack initiation will occur. Thirdly, the material must experience a sufficiently large number of cycles of the applied stress. The number of cycles required to initiate and grow a crack is largely dependant on the first to factors.

In addition to these three basic factors, there are a host of other variables, such as stress concentration, corrosion, temperature, overload, metallurgical structure, and residual stresses which can affect the propensity for fatigue. Since fatigue cracks generally initiate at a surface, the surface condition of the component being loaded will have an effect on its fatigue life. Surface roughness is important because it is directly related to the level and number of stress concentrations on the surface. The higher the stress concentration the more likely a crack is to nucleate. Smooth surfaces increase the time to nucleation. Notches, scratches, and other stress risers decrease fatigue life. Surface residual stress will also have a significant effect on fatigue life. Compressive residual stresses from machining, cold working, heat treating will oppose a tensile load and thus lower the amplitude of cyclic loading.

The figure shows several types of loading that could initiate a fatigue crack. The upper left figure shows sinusoidal loading going from a tensile stress to a compressive stress. For this type of stress cycle the maximum and minimum stresses are equal. Tensile stress is considered positive, and compressive stress is negative. The figure in the upper right shows sinusoidal loading with the minimum and maximum stresses both in the tensile realm. Cyclic compression loading can also cause fatigue. The lower figure shows variable-amplitude loading, which might be experienced by a bridge or airplane wing or any other component that experiences changing loading patterns. In variable-amplitude loading, only those cycles exceeding some peak threshold will contribute to fatigue cracking. S-N Fatigue Properties.

There are two general types of fatigue tests conducted. One test focuses on the nominal stress required to cause a fatigue failure in some number of cycles. This test results in data presented as a plot of stress (S) against the number of cycles to failure (N), which is known as an S-N curve. A log scale is almost always used for N.

The data is obtained by cycling smooth or notched specimens until failure. The usual procedure is to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles, which is usually at least 107 cycles. The highest stress at which a runout (non-failure) occurs is taken as the fatigue threshold. Not all materials have a fatigue threshold (most nonferrous metallic alloys do not) and for these materials the test is usually terminated after about 108 or 5×108 cycles.

Since the amplitude of the cyclic loading has a major effect on the fatigue performance, the S-N relationship is determined for one specific loading amplitude. The amplitude is express as the R ratio value, which is the minimum peak stress divided by the maximum peak stress. (R= σmin/σmax). It is most common to test at an R ratio of 0. 1 but families of curves, with each curve at a different R ratio, are often developed.

A variation to the cyclic stress controlled fatigue test is the cyclic strain controlled test. In this test, the strain amplitude is held constant during cycling. Strain controlled cyclic loading is more representative of the loading found in thermal cycling, where a component expands and contracts in response to fluctuations in the operating temperature.

It should be noted that there are several short comings of S-N fatigue data. First, the conditions of the test specimens do not always represent actual service conditions. For example, components with surface conditions, such as pitting from corrosion, which differs from the condition of the test specimens will have significantly different fatigue performance. Furthermore, there is often a considerable amount of scatter in fatigue data even when carefully machined standard specimens out of the same lot of material are used. Since there is considerable scatter in the data, a reduction factor is often applied to the S-N curves to provide conservative values for the design of components.

Introduction to Materials:

This section will provide a basic introduction to materials and material fabrication processing. It is important that NDT personnel have some background in material science for a couple of reasons. First, nondestructive testing almost always involves the interaction of energy of some type (mechanics, sound, electricity, magnetism or radiation) with a material. To understand how energy interacts with a material, it is necessary to know a little about the material. Secondly, NDT often involves detecting manufacturing defects and service induced damage and, therefore, it is necessary to understand how defects and damage occur.

This section will begin with an introduction to the four common types of engineering materials. The structure of materials at the atomic level will then be considered, along with some atomic level features that give materials their characteristic properties. Some of the properties that are important for the structural performance of a material and methods for modifying these properties will also be covered.

In the second half of this text, methods used to shape and form materials into useful shapes will be discussed. Some of the defects that can occur during the manufacturing process, as well as service induced damage will be highlighted. This section will conclude with a summary of the role that NDT plays in ensuring the structural integrity of a component.

In materials science, fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and is one of the most important properties of any material for virtually all design applications. It is denoted KIc and has the units of .

The subscript ‘ Ic’ denotes mode I crack opening under a normal tensile stress perpendicular to the crack, since the material can be made thick enough to resist shear (mode II) or tear (mode III).

Fracture toughness is a quantitative way of expressing a material’s resistance to brittle fracture when a crack is present. If a material has a large value of fracture toughness it will probably undergo ductile fracture. Brittle fracture is very characteristic of materials with a low fracture toughness value. [1]

Fracture mechanics, which leads to the concept of fracture toughness, was largely based on the work of A. A. Griffith who, among other things, studied the behavior of cracks in brittle materials.

Crack growth as a stability problem:

Consider a body with flaws (cracks) that is subject to some loading; the stability of the crack can be assessed as follows. We can assume for simplicity that the loading is of constant displacement or displacement controlled type (such as loading with a screw jack); we can also simplify the discussion by characterizing the crack by its area, A. If we consider an adjacent state of the body as being one with a larger crack (area A+dA), we can then assess strain energy in the two states and evaluate strain energy release rate.

The rate is reckoned with respect to the change in crack area, so if we use U for strain energy, the strain energy release rate is numerically dU/dA. It may be noted that for a body loaded in constant displacement mode, the displacement is applied and the force level is dictated by stiffness (or compliance) of the body. If the crack grows in size, the stiffness decreases, so the force level will decrease. This decrease in force level under the same displacement (strain) level indicates that the elastic strain energy stored in the body is decreasing – is being released. Hence the term strain energy release rate which is usually denoted with symbol G.

The strain energy release rate is higher for higher loads and larger cracks. If the strain energy so released exceeds a critical value Gc, then the crack will grow spontaneously. For brittle materials, Gc can be equated to the surface energy of the (two) new crack surfaces; in other words, in brittle materials, a crack will grow spontaneously if the strain energy released is equal to or greater than the energy required to grow the crack surface(s). The stability condition can be written as;

Elastic energy released = surface energy created:

If the elastic energy releases is less than the critical value, then the crack will not grow; equality signifies neutral stability and if the strain energy release rate exceeds the critical value, the crack will start growing in an unstable manner. For ductile materials, energy associated with plastic deformation has to be taken into account. When there is plastic deformation at the crack tip (as occurs most often in metals) the energy to propagate the crack may increase by several orders of magnitude as the work related to plastic deformation may be much larger than the surface energy. In such cases, the stability criterion has to restated as;

Elastic energy released = surface energy + plastic deformation energy;

Practically, this means a higher value for the critical value Gc. From the definition of G, we can deduce that it has dimensions of work (or energy) /area or force/length. For ductile metals GIc is around 50 to 200 kJ/m2, for brittle metals it is usually 1-5 and for glasses and brittle polymers it is almost always less than 0. 5. The I subscript here refers to mode I or crack opening mode as described in the section on fracture mechanics.

The problem can also be formulated in terms of stress instead of energy, leading to the terms stress intensity factor K (or KI for mode I) and critical stress intensity factor Kc (and KIc). These Kc and KIc (etc) quantities are commonly referred to as fracture toughness, though it is equivalent to use Gc. Typical values for KIcare 150 MN/m3/2 for ductile (very tough) metals, 25 for brittle ones and 1-10 for glasses and brittle polymers. Notice the different units used by GIc and KIc. Engineers tend to use the latter as an indication of toughness.

Transformation toughening:

Composites exhibiting the highest level of fracture toughness are typically made of a pure alumina or some silica-alumina (SiO_2 /Al_2O_3) matrix with tiny inclusions of zirconia (ZrO_2) dispersed as uniformly as possible within the solid matrix. (*Note: a wet chemical approach is typically necessary in order to establish the compositional uniformity of the ceramic body before firing).

The process of “ transformation toughening” is based on the assumption that zirconia undergoes several martensitic (displacive, diffusionless) phase transformations (cubic → tetragonal → monoclinic) between room temperature and practical sintering (or firing) temperatures. Thus, due to the volume restrictions induced by the solid matrix, metastable crystalline structures can become frozen in which impart an internal strain field surrounding each zirconia inclusion upon cooling. This enables a zirconia particle (or inclusion) to absorb the energy of an approaching crack tip front in its nearby vicinity.

Thus, the application of large shear stresses during fracture nucleates the transformation of a zirconia inclusion from the metastable phase. The subsequent volume expansion from the inclusion (via an increase in the height of the unit cell) introduces compressive stresses which therefore strengthen the matrix near the approaching crack tip front. Zirconia “ whiskers” may be used expressly for this purpose.

Appropriately referred to by its first dicoverers as “ ceramic steel”, the stress intensity factor values for window glass (silica), transformation toughened alumina, and a typical iron/carbon steel range from 1 to 20 to 50 respectively.

Conjoint action:

There are number of instances where this picture of a critical crack is modified by corrosion. Thus, fretting corrosion occurs when a corrosive medium is present at the interface between two rubbing surfaces. Fretting (in the absence of corrosion) results from the disruption of very small areas that bond and break as the surfaces undergo friction, often under vibrating conditions. The bonding contact areas deform under the localised pressure and the two surfaces gradually wear away. Fracture mechanics dictates that each minute localised fracture has to satisfy the general rule that the elastic energy released as the bond fractures has to exceed the work done in plastically deforming it and in creating the (very tiny) fracture surfaces. This process is enhanced when corrosion is present, not least because the corrosion products act as an abrasive between the rubbing surfaces.

Fatigue is another instance where cyclical stressing, this time of a bulk lump of metal, causes small flaws to develop. Ultimately one such flaw exceeds the critical condition and fracture propagates across the whole structure. The ‘ fatigue life’ of a component is the time it takes for criticality to be reached, for a given regime of cyclical stress. Corrosion fatigue is what happens when a cyclically stressed structure is subjected to a corrosive environment at the same time. This not only serves to initiate surface cracks but (see below) actually modifies the crack growth process. As a result the fatigue life is shortened, often considerably.

Stress-corrosion cracking (SCC):

Main article: Stress corrosion cracking:

This phenomenon is the unexpected sudden failure of normally ductile metals subjected to a constant tensile stress in a corrosive environment. Certain austenitic stainless steels and aluminium alloys crack in the presence of chlorides, mild steel cracks in the present of alkali (boiler cracking) and copper alloys crack in ammoniacal solutions (season cracking). Worse still, high-tensile structural steels crack in an unexpectedly brittle manner in a whole variety of aqueous environments, especially chloride. With the possible exception of the latter, which is a special example of hydrogen cracking, all the others display the phenomenon of subcritical crack growth, i. e. small surface flaws propagate (usually smoothly) under conditions where fracture mechanics predicts that failure should not occur. That is, in the presence of a corrodent, cracks develop and propagate well below KIc. In fact, the subcritical value of the stress intensity, designated as KIscc, may be less than 1% of KIc,

The subcritical nature of propagation may be attributed to the chemical energy released as the crack propagates. That is,

Elastic energy released + chemical energy = surface energy + deformation energy:

The crack initiates at KIscc and thereafter propagates at a rate governed by the slowest process, which most of the time is the rate at which corrosive ions can diffuse to the crack tip. As the crack advances so K rises (because crack length appears in the calculation of stress intensity). Finally it reaches KIc , whereupon fast fracture ensues and the component fails. One of the practical difficulties with SCC is its unexpected nature. Stainless steels, for example, are employed because under most conditions they are ‘ passive’, i. e. effectively inert. Very often one finds a single crack has propagated while the rest of the metal surface stays apparently unaffected.

See also:

- Fracture.
- Fracture mechanics.
- Brittle-ductile transition zone.
- Charpy impact test.
- Izod impact strength test.
- Toughness of ceramics by indention.
- Stress corrosion cracking.
- Toughness.

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A fracture is the (local) separation of an object or material into two, or more, pieces under the action of stress.

The word fracture is