Theory of tensile test engineering essay

Tensile test is a standard engineering procedure to characterize properties related to mechanical behavior of materials. The properties describe the response of the material during the actual loading conditions. The variation in geometry of the specimen has to be considered. Although the behavior of the material inside elastic limit is of considerable importance but the knowledge beyond elastic limit is also relevant but plastic effects with large deformation takes place in number of manufacturing processes. The Fracture toughness acts to stop the progress of fracture in a material. Fracture toughness vary according to the loading rate, environment, temperature, the composition of material and its microstructures together with geometric effects. These factors are important for welded joints when metallurgical and geometrical effects are complex.

Theory of Tensile Test, elastic constant, surface energy, fracture toughness and derivation of fatigue potential energy, lethargy coefficient, surface energy per unit area / per unit mole, and fracture toughness using dynamic fatigue. life equation are presented in this chapter.

2. 2 TENSILE TEST

The engineering Tensile Test is also known as tension test which vary widely used for providing the base of the design information on the strength of material and as an acceptance test for the specification of the materials. Tensile Tests are very simple, relatively, inexpensive, and fully standardized. Under the pulling type of loading something, it can be very quickly determined how the material will react to the these type of forces being applied in tension. As the materials are being pulled, its strength and elongation can be find out. A lot of about a substance can be learned from tensile testing. As the machine continues to pull on the material until it breaks, a good, complete tensile profile is obtained. The curve shows how it reacted to the forces being applied. In the tension test a specimen is subjected to a continually increasing one directional tensile force while simultaneous observations are made of the elongation of the ductile specimen. Fig 2. 1 shows a typical stress-strain diagram for mild steel.

Fig 2. 1: Typical Stress-Strain Curve for mild steel [1]

A: Proportional limit

B: Elastic limit

C: Upper yield point

D: Lower yield point

E: Ultimate stress point

F: Breaking point

Proportional limit: Stress is a linear function of strain and the material obeys Hooke’s law. This proportionality extends upto point A and this point is called proportional limit or limit of proportionality. O-A is a straight line portion of the curve and its slope represents the value of modulus of elasticity.

Elastic limit: Beyond proportional limit, stress and strain depart from straight line relationship. The material however, remains elastic upto state point B. The word elastic implies that the stress developed in the material is such that there is no residual or permanent deformation when the load is removed. Upto to this point, the deformation is reversible or recoverable. Stress at B is called the elastic limit stress; this represents the maximum unit stress to which a material can be subjected and is still able to return to its original form upon removal of load.

Yield point: Beyond elastic limit, the material shows consideral strain even though there is no increase in load or stress. This strain is not fully recoverable, i. e., there is no tendency of the atoms to return to their original position. The behavior of the material is inelastic and the onset of plastic deformation is called yielding of the material. The point C is called the upper yield point and point D is the lower yield point. The difference between the upper and lower yield point is small and the quoted yield stress is usually the lower value.

Ultimate strength or tensile strength: After yielding has taken place, the material becomes strain hardened (strength of the specimen increases) and an increase in load is required to take the material to its maximum stress at point E. Strain in this portion is about 100 times than that of the portion from O to D. Point E represents the maximum ordinate of the curve and the stress at this point is known either as ultimate stress or the tensile stress of the material.

Breaking strength: In the portion EF, there is falling off the load (stress) from the maximum until fracture takes place at F. The point F is referred to as the fracture or breaking point and the corresponding stress is called the breaking stress [1].

The stress-strain curve is constructed from the load-elongation measurements (fig. 2. 2). The stress used in this stress-strain profile is the average longitudinal stress in the Tensile Test. It can be obtained by dividing the load by original area of cross-section of the specimen.

Stress = (2. 1)

The strain used for the engineering stress-strain curve is the average linear strain, which is the rate of the elongation of gauge length of the specimen, and its original length.

= = = (2. 2)

Fig 2. 2: The Engineering Stress-Strain Curve [2]

The magnitude and shape of the stress-strain curve of a metal will depend upon its prior history of plastic deformation, heat treatment, composition , and the strain rate, temperature, and state at which stress imposed during the testing. The different type of parameters which are used to describe the stress-strain curve of a metal are the percentage elongation, reduction of area, tensile strength and yield strength. The first two are ductility; the last two indicates strength parameters. In the zone of elastic limit, strain is measured by an “ extensometer” attached to the gauge length.

In the elastic limit stress is linear proportional to strain. When the load exceeds a value above the yield strength, the specimen undergoes to plastic deformation. It is permanently deformed if the load is released to zero. The stress, to produce continuous plastic deformation, increases with increasing plastic strain i. e. the metal strain-hardens [2] .

The volume of the specimen remains constant during plastic deformation,

= o o (2. 3)

Where

= Final area of cross section of specimen

= Final length of specimen

o = Original area of cross section of specimen

o = Original length of specimen

And as specimen elongates, due to this it decreases uniformly in cross sectional area. At the beginning the strain hardening more than compensates for this decrease in area and the engineering stress continues rises with increasing strain finally a point is arrived where the effect of decrease in specimen cross-sectional area is higher than the increase in deformation load arising from the strain hardening. This typical condition reaches first at some point in the specimen that is slightly weaker than the rest. The further non elastic deformation is concentrated in this region, and the specimen begins to neck or thin down locally. For the reason that the cross-sectional area now is decreasing far more rapid rate than the deformation load is increased by strain hardening, the actual amount of load required to deform the specimen falls and the engineering stress in the same way continues to decrease until fracture occurs. Many varieties of fractures can occur during the processing of metals and their use in different types of application. One of them is the Ductile Fracture. [3]

2. 2. 1 DUCTILE FRACTURE

Ductile fracture has been defined as fracture occurring with appreciable gross deformation. Ductile fracture in tension is usually defined by a localized reduction in diameter called necking. Very ductile metals may actually draw down to a line or a point before separation. This kind of failure is usually called by rupture.

Consider segment of a cylindrical bar of length , cross-sectional area A0 and subjected to a load as shown in fig 2. 3(a) when the load is increased to 12 and further to , the area of cross-section decreases to 12 and and length elongates to 12210 as shown in figs. 2. 3 b-c-d. The conventional stress and conventional strain are obtained in each case by

It clearly shows that the original A is assumed constant . This criteria may be true for elastic range only as elastic reduction in cross-sectional area is negligible , being only about 0. 1% . The strains are also very small.

However, while dealing with the plastic range, the reduction in cross-sectional area and the strain are large (compare Fig. 2. 3 a and b). Hence cannot be taken as constant, and may not be used for strain calculations at all the loads. Thus the need arises to obtain true stress and true strain in plastic range. These are determined in steps as follows [4].

Fig 2. 3: Stages in the formation of a cup-and-cone fracture [4].

2. 3 Universal Testing Machine

The servo hydraulic testing machines provide both load controlled and displacement control machine. These versatile machines are well adapted to computer control. With modern computer control it is possible to conduct tests based on the control of calculated variables such as true strain or stress intensity factor. Fig2. 4 shows a picture of Universal Testing Machine.

In UTM top cross head can be adjusted to three positions for extended tension tests (the left hand side of the machine). There are two main hand wheel controls, one for applying and the other for releasing the load. The loading valve is designed in so manner that at any setting, needed for applying incremental loads, for applying the loads quickly, for holding the loads steady and for removing the loads. An autographic recorder is used to plot the stress-strain curve during the test itself.

Specimens are attached to a movable grip and to a fixed side-gripping device. A parallel spring is made of four thin plates to serve as the straight guide mechanism for the movable grip. The movable grip and straight guide mechanism are lifted over the base of the tensile testing machine so that they were not affected by friction which would otherwise seriously impair the accuracy of the Tensile Tests. Load is applied by pulling (using a precision translation stage driven by a D. C. motor) one end of steel belt, the other end, is connected to the movable grip. A load cell with a rated capacity is used to measure the load, which is the sum of the loads applied to the specimen and parallel spring. The load applied or the specimen is calculated by subtracting the load applied to the parallel spring, calculated from the

Fig 2. 4: Universal Testing Machine. [3]

Characteristics of the parallel spring measure in advance, from the measure load. The elongation was determined by measuring the relative displacement of the two gauge marks on the specimen. The characteristics of the testing machine have a strong influence on the shape of the stress-strain diagram and the fracture behavior a rigid testing machine with a spring constant is known as a hard machine. A screw-driven mechanical machine tends to be hard machines, while hydraulically driven testing machines are soft machines. A hard testing machine produces the upper and lower yield point, but in a soft machine only the extension at constant load will be recorded.

Universal Testing Machine is used to conduct the Tensile Test. There are two types of machines used in tension testing.

1. Load controlled machine

2. Displacement controlled machines [3].

2. 4 ELASTIC CONSTANT

Materials may be isotropic, orthotropic, and anisotropic. Isotropic materials posses four elastic constants named Young's modulus Poisson's ratio shear modulus and bulk modulus These constants are invariant and do not ordinarily change under any effect .

Strain and stress on basis of atomic theory

Force versus distance of atomic separation curve and bond length described in fig 2. 5. The inter-atomic equilibrium distance decreases to when a compressive force is applied. Similarly on application of a tensile force the inter-atomic equilibrium distance decreases to this externally applied force is equal in magnitude but opposite in nature of inter-atomic force Therefore

(2. 4)

Fig 2. 5: Change in inter atomic distance on application of compressive forces [5].

Where is the potential energy which in the most general way can be expressed as

(2. 5)

Hence are constant in which . The increase in length of interatomic

distance is called elongation, and is given by

to (2. 6)

Similarly the decrease in length of inner -atomic distance is called contraction , and it is express as,

(2. 7)

(a). The Strain is then defined as the change in length of inter atomic distance over bond length . The tensile strain Îµt and compressive strain Îµc are related as [5]

Îµt = =

and Îµc = =

(b). The Stress Ïƒ is defined as the internal resisting force i. e. inter atomic force F per unit cross sectional area A of a material. Therefore

Ïƒ =

Due to Eqs. 2. 4 and 2. 5 it can be written as

Ïƒ = = = (2. 8)

The stress can be either tensile or compressive in nature.

Poisson's Ratio: A material, subjected to a tensile stress, elongates in the direction of tensile axis but contracts in the transverse direction the transverse strains always bear a constant ratio, with the longitudinal strain. This ratio is called Poisson's ratio and is expressed by

(2. 9)

Young's modulus: In the fig 2. 5 a tangent is drawn at . It coincide with the curve over a small range and . AB is in elastic region. This slope is proportional to the young's modulus E of a material, Thus [5]

It may be approximated that the force acts on area which is the average area per atom since number of bonds per unit area is 1/ and also knowing macroscopically that stress is proportional to strain within elastic limit (Hooke's law),

(2. 10)

(2. 11)

The young's modulus is also known as modulus of elasticity or elastic modulus. Its value for a material is influenced by factor such as bonding character, temperature, and anisotropy strongly bonded solids with three – dimensional network possess high values of elastic modulus [5]. The effect of temperature is to lower down the elastic modulus by 10% to 20% between 0 K to melting point . The variation of as a function of temperature for carbon steel can be expressed by

(2. 12)

Where is in Kelvin and is in kgf/cm2

Shear Modulus: The ratio of shear stress and the shear strain Î³ is defined as shear modulus or modulus of rigidity It is related to the Young’s modulus and Poisson’s ratio by

(2. 13) Bulk Modulus: A material under three dimensional loading is subjected to the stresses axes respectively. The initial volume of the material changes by then lk modulus or modulus of elasticity of volume is defined as the ratio of average stress to volumetric strain and is expressed by [5]

(2. 14)

Where (2. 15)

And (2. 16)

(2. 17a)

(2. 17 b)

(2. 17c)

Here are the linear strains along axes respectively. is related to and by

= (2. 18)

The three elastic modulii are related as

(2. 19a)

In materials such as gels, pastes, putties and colloidal system, therefore

(2. 19b)

2. 5 FRACTURE TOUGHNESS

Fracture toughness, is defined as resistance of a material to failure from fracture starting from preexisting crack. Mathematically, it is expressed as

= (2. 20)

Where is a dimensionless factor which depends upon the following:

The geometry of the crack and material.

2. The loading configuration if the sample is subject to tension or bending.

3. The ratio of crack length to specimen width.

4. Amount of load (stress) applied to the specimen

Where = crack length.

= width of specimen

Fig 2. 6: A specimen with an interior crack [6].

Note that the entire crack length is equal to ‘ a’

Fig 2. 7: A specimen with a through-thickness crack [6].

Fig 2. 8: A specimen with a half circle surface crack [6].

Figure 2. 6 shows that a is not always the total length of the crack, but sometimes it is half of the crack length in case of Interior crack [6]. The values for Y vary with respect to the shape and location of the crack. Some important values of Y for short cracks subjected to a tension load are as follows:

For an interior crack which is shown in fig 2. 6.

For a through-thickness surface crack which is shown in fig 2. 7

For a half-circular surface crack which is shown in fig 2. 8

Fracture toughness, has the English customary units of psi inch1/2, and the SI units of MPa m1/2

2. 5. 1 Plane strain fracture toughness

For thin samples, the value decreases with increasing sample thickness, b, as shown in Figure 2. 9. Finally, becomes independent of b, called as the conditions of plane strain. This fixed value of becomes known as the plane strain fracture toughness. Mathematically, it is expressed as:

= [7]. (2. 21)

Fig 2. 9: A fracture toughness vs. thickness graph [7].

This value for the fracture toughness is the value normally specified because it is never greater than or equal to. The I subscript for, stands for mode I, or tensile mode [7].

2. 5. 2 Fracture toughness testing machine

A sharp fatigue crack(break) is inserted in the specimen, which is loaded to failure. The crack driving force is measured for the failure condition, giving the fracture toughness [9].

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Fig 2. 10: Fracture mechanics testing. [9]

2. 5. 3 Test specimens for fracture toughness

The mostly uses fracture toughness test configurations are the single sharp edge notch bend (SENB or three-point bend), and the compact (CT) specimens, as shown in fig 2. 11. These type of compact specimen has the advantage that it requires less amount of material, but is more expensive to machine and more difficult to test compared with the SENB specimen. Special requirements are needed for temperature control, for this purpose we use an environmental chamber. The SENB specimens are typically immersed in a bath for low temperature tests. Although the compact specimen is loaded in tension, the crack tip conditions are predominantly bending (high constraint). If limited materials are available, it is possible to construct the SENB specimens by welding extension pieces (for the loading arms) to the material sample.

(Electron beam welding(EBW) is typically used, because the weld is narrow and causes little distortion).

Fig 2. 11: Examples of common fracture toughness test specimen

(a) SENB Specimen (b) CT Specimen [10].

Other specimen configurations are the centre-cracked tension (CCT) panels, single edge notch tension (SENT) specimens, and shallow-crack tests. These special types of tests are connected with lower levels of constraint, and can be more structurally representative than standard CT or SENB specimens. The SENT specimens are being used to determine fracture toughness of pipeline girth in submarine pipelines, especially where the installation method involves plastic straining. The position and orientation of the specimens are important. The location and orientation of the notch is critical, especially for welded joints. The orientation of the notch is defined with respect to either the weld axis or the rolling direction or forging axis of other components. In the standard SENB & C T specimens are shown in Fig 2. 11, the notch depth is range of 45 to 70% of the specimen width, W, giving a lower-bound conservative estimate of fracture toughness, because of the high level of crack tip constraint generated by the specimen design only [10].

2. 5. 4 Fracture toughness Measurement

Fig 2. 12: Two ASTM standard compact specimen of different Widths (b). [8]

There are many different experiments which can be used to obtain a value of. Almost any size and shape of sample can be used as long as it is consistent with mode I crack displacement. A possible and very simple experiment that can be performed to find a value for fracture toughness by screw-driven universal testing machine. This testing machine loads the specimen, at a constant strain rate, while a Load vs. Displacement curve is plotted by an X-Y recorder. From this plot, a possible value for Y can be calculated. With this value can be calculated. [8]

2. 5. 5 Effect of temperature on fracture toughness

Fracture toughness varies with temperature, crack size and crack location and does not change with sample thickness. Fracture toughnessdoes also vary with strain rate, shown in figure 2. 13 [9]

Fig 2. 13 : Fracture Toughness vs. Temperature for several steels. [9]

2. 6 SURFACE ENERGY

Surface energy is defined as the potential energy per unit area of surface film. It may be also defined as the amount of work done in increasing the area of the surface film through unity. Surface energy per unit area is also known as surface tension of liquid [11].

2. 6. 1 Surface energy measurement of the solid

The surface energy of a liquid may be measured by stretching a liquid membrane (which increases the surface area and hence also the surface energy density). In that case, in order to increase the surface area of a mass of the liquid by an amount, , a quantity of work, is needed (where is the surface energy density of the liquid). However, such a method cannot be used to measure the surface energy of a solid materials for the reason that stretching of a solid membrane induces elastic energy in the bulk in addition to increasing the surface energy. The surface energy of a solid is usually measured at high temperatures. At such temperatures the solid creeps and even though the surface area changes, the entire volume remains approximately constant [11].

2. 7 FATIGUE POTENTIAL ENERGY (U0) AND LETHARGY COEFFICIENT (Î³)

The dynamic fatigue equation for high-cycle fatigue under fully reversed tension-compression loading is given by [12].

= constant (2. 18).

From Eq. (2. 18) we can say that

(2. 19)

Where is alternating stress amplitude that gives and= 1

Eq. (2. 18) is rewritten as

€ (2. 20)

Lethargy coefficient can be calculated from S-N curve, to the a variation of stress amplitude to the logarithm of number of cycles to failure, as shown in fig 2. 14

Fig 2. 14: The S-N curve [12].

2. 8 MICROSTRUCTURAL PROCESS UNDER HIGH-CYCLE FATIGUE LOADING

For high-cycle fatigue conditions, stress amplitude is below yield strength of the material, so that the strain is normally elastic. If strain is purely elastic, These will be no fatigue because elastic straining is, a reversible process. However, this difficulty is associated with over-simplification introduced by concept of a yield strength and assumption of purely elastic deformation below this yield strength. All metals undergo a minor amount of plastic strain even at low stresses. This is called microstrain, because at stresses well below yield strength the magnitude of plastic strain is small as compare to elastic strain. Microscopic examination of surfaces of samples that have been subjected to cyclic loading reveals that micro strain occurs in homogeneously in the sample, with the entire strain seemingly concentrated in a relatively few slip bands. These slip bands form during the first few thousand cycles and remain active until after a crack is formed. Because straining in these bands continues after the bulk of material has stopped undergoing strain, they are called persistent slip bands. Since the strain is so inhomogeneous, plastic strain amplitude in persistent slip bands is quite large compared to average strain amplitude. Thus damage accumulation leading to crack formation can continue in persistent slip bands at very low average plastic strain amplitude. The nature of damage which leads to crack formation in high cycle fatigue seems to be related to formation of intrusions and extrusions within slip bands. In this phenomenon, material is pushed out of surface at one point in the band and material is drawn in to form deep valleys at other points in the bands. Once a true crack has formed in a material, the presence of the crack itself dominates the stress and strain behavior in its vicinity. The development of the theory of fracture mechanics to describe the behavior of bodies which contain cracks has been quite useful in reaching an understanding of the process of crack propagation in fatigue [13].

2. 9 SURFACE ENERGY AND FRACTURE TOUGHNESS

The Arrhenius model for the fatigue life equation and Zhurkov's static fatigue equation are of the same type, given as [14]

= (2. 21)

Where

= fatigue life of the material

= material constant

= Kelvin temperature

= bonding energy constant of material

= lethargy coefficient

= function of dynamic fatigue model

The fraction of the life already passed by as follows ,

(2. 22)

= fraction of the life passed in the time interval dt.

The whole life is integrated like

= 1 (2. 23)

In ordinary uniaxial Tensile Test, it is assumed that temperature is constant and that the stress increases linearly

Eq. (2. 23) becomes

Where is the time from the start of loading up to fracture. Because fracture begins at the ultimate tensile strength, the stress is maximum at

Eq. (2. 23) is simplified as

(2. 24)

The surface energy per mole is defined as

(2. 25)

and the surface energy per unit area as

= (2. 26)

Where surface energy per unit area for elastic brittle fracture

is the time for elastic brittle fracture

In terms of displacement, the surface energy is given as

= (2. 27)

Eq. (3. 27) can be written as

= (2. 28)

Finally fracture toughness may be given as

. (2. 29)

2. 10 CONCLUDING REMARKS

In this chapter we have discussed that fracture toughness is very important for welded joints where geometric effects are complex . Theory of Tensile Test, elastic constant and surface energy and fracture toughness are presented in this chapter. The derivation of fatigue potential energy, lethargy coefficient, and surface energy per unit area, surface energy per unit mole and fracture toughness from dynamic fatigue equation are carried out.