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THE ROLE OF MECHANICAL PROPERTIES OF METALS IN ENGINEERING DESIGN

By L.N. Pussegoda

Introduction

Development is a result of technological advances. The introduction of new materials, higher operating speeds, higher temperatures, lighter weight, smaller volume, lower cost and improved ecological compatability, all demand better engineering design techniques. Therefore it is becoming important to identify the mode of failure of component/structure/machine under the specific conditions of operation (loading, environment etc.)

The most frequent premature failure of metal components in today's engineering industry are associated with brittle modes. These are usually a result of "dynamic" (fluctuating) loads which cause fatigue failure, and "critical" pre-existing crack-like flaws in metal which propagate rapidly under "static" loads.

The aim of this paper is to provide the design engineer with introductory information on the mechanical properties of metals associated with common modes of failure. Other important factors that play a major role in engineering design in order to avoid the operative failure mode are also introduced.

Philosophy of Engineering Design

Engineering designs are usually based on the concept of failure. The design criterion can be either no failure or failure after a predetermined period of useful operation. In the latter case the consequence of failure in terms of human life/property has to be taken into consideration. In an "ideal" or "perfect" design all components of a structure/machine must fail exactly at the design life. There are many reasons why such a design is not possible and perhaps not even desirable, even though it would be an absolute "optimum" in the context of material utilization.

Therefore, it is essential to establish the "critical" components of a design, and the desired modes of their failure. For example, the design criterion for an automobile can be either the failure of the engine due to wear or of the body/chassis due to corrosion, but not the failure of the steering column due to fatigue. Another example is the rerequirement of a ductile mode of failure in reinforced concrete structural design giving sufficient warning of the impending failure.

Other important factors are:-

1. Economic worthwhileness; the design must be competitive in the market place.

2. Optimization; the design must be optimal from the available alternatives.

STRUCTURAL OR MECHANICAL FAILURE

Structural or mechanical failure may

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be defined as any change in size, shape, material properties of a structure, machine or machine part that makes it incapable of satisfactorily performing its intended function. Therefore success in designing competitive products can be achieved only by recognizing and evaluating all potential modes of failure that might govern the design. If premature failure is to be avoided the designer must have a good working knowledge of analytical and/or empirical techniques of predicting failure. When these failures are associated with metals, the mechanical properties of metals will play an important role in engineering design.

Given below are the more common modes of metal failure.

1. Yielding; in elastic design where stresses in components exceed the yield stress.

2. Ductile fracture; in ductile metals when the stresses exceed the ultimate tensile strength.

3. Brittle fracture; catastrophic failure usually under elastic loading. Design based on "fracture toughness".

4. Fatigue; catastrophic failure under fluctuating stresses. Design based on "fatigue strength".

5. Corrosion; deterioration of metal as a result of chemical or electrochemical interaction with the environment. Corrosion often interacts with other failure modes such as brittle fracture (stress corrosion cracking, hydrogen embrittlement etc.) and fatigue (corrosion fatigue).

6. Wear; metal removal from contacting surfaces through a complex combination of local shearing, plowing, gouging, welding, tearing etc. Common forms of wear are adhesive wear, abrasive wear and corrosion wear

7. Fretting; surface damage due to debris trapped between surfaces in contact. Failure takes place in combination with other failure modes, eg:- fretting wear, fretting corrosion and fretting fatigue.

8. Creep; accumulation of plastic deformation over a period of time under stress and high temperature (between 0.35 T_m and 0.7 T_m, T_m (°K) is melting temperature). Final fracture due to creep is known as creep rupture (sometimes known as stress rupture).

9. Buckling; elastic instability of slender compression members.

10. Combination modes; eg:- corrosion fatigue, creep fatigue, and corrosion-creep-fatigue. These failure modes are critical in the design of gas turbines, chemical processing plants, power generation plants etc.

Basic Mechanical Properties of Metals

The failure modes outlined earlier can be related to basic mechanical properties of metals, environmental effects on these properties, geometry of the component, and loading conditions.

TENSILE PROPERTIES

Fig. 1 shows the two categories of stress-strain curves that are obtained for metals; ferrous and non-ferrous. The important properties are yield strength (Y.S.) (or 0.2% proof strength), tensile strength (T.S.) and elongation (EL). Standard testing procedures are given in BS 18: Part 1: 1970 and BS 18: Part 2:1971.

TOUGHNESS

A measure of the energy required for fracture. In a tensile test that is the area under the stress-strain curve. Standard method of testing to obtain toughness are given below.

(1) Izod Impact Testing
Determination of energy absorbed at room temperature by a standard notched specimen using a standard impact testing procedure

given in BS 131: Part 1:1961. This test is useful for comparison purposes.

(2) Charpy V-notch Impact Testing

Determination of the absorbed impact energy variation with testing temperature by a standard notched specimen using a standard impact testing procedure given in BS 131: Part 2: 1972. This test is useful for metals which show a change in fracture mode from ductile (high energy fracture) to brittle (low energy fracture) in a small temperature range (transition temperature range). A typical variation shown in Fig. 2 is characteristic for metals with a body centered cubic (bcc) cell structure. The major significance of this test is that it high-lights the fact that metals (eg: ferrous metals) can be ductile at room temperature while brittle at low temperatures.

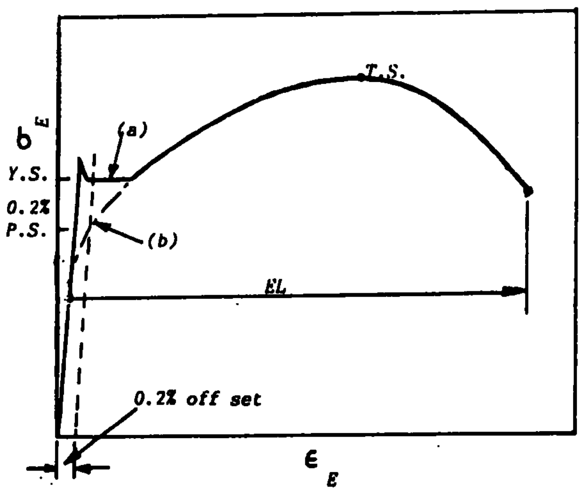

Fig. 1 Engineering stress - engineering strain curves for (a) Ferrous, and (b) Nonferrous metals.

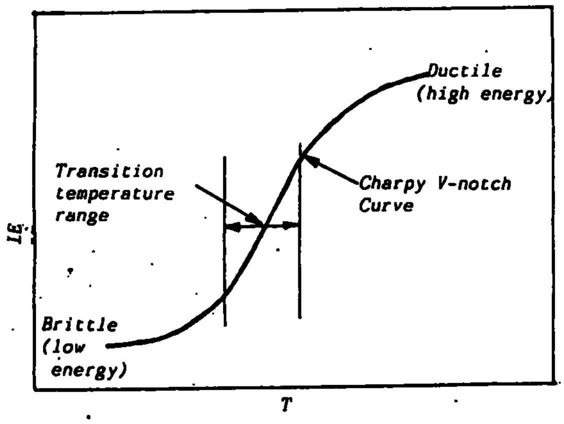

Fig. 2

Variation of impact energy (IE) with testing temperature (T) of a metal with body centered cubic (bcc) cell structure.

(3) Fracture toughness testing

The determinations made using earlier toughness tests (i.e. (1) and (2)) do not give a quantitative design criterion like the yield strength, which is a meterial property. This limitation has been partially solved by the development of 'Fracture Mechanics'.

The essence of the fracture toughness test is given below.

(a) A standard specimen with a previously introduced flow (usually a fatigue crack) is loaded. The "stress intensity factor" at the crack tip may be given by,

$$K = C\,\sigma\sqrt{\pi\alpha}$$

Where C - is dependent on the type of loading and geometry away from the crack

α - crack length, and

σ - nominal stress.

(b) For a fixed crack length 'a' when σ_c reached a critical value σ_c the crack propagates abruptly to failure. Fig. 3 shows the typical variation of σ_c with 'a'

(c) The critical stress intensity factor K_c $\left(= C\,\sigma_c\sqrt{\pi\alpha}\right)$ is a material property termed "fracture toughness"

(d) Fracture toughness testing is carried out in order to determine K_c. Failure is predicted for (σ, α) combinations which give $K \geqslant K_c$ (see Fig. 3), and hence can be used similar to the yield strength as a design criterion. The value of K_c is influenced by temperature, loading rate, and environment.

$K = C\,\sigma\sqrt{\pi\alpha}$ is determined by a 2D/3D stress analysis for a linear elastic material in the context of "linear elastic fracture mechanics" (LEFM). The validity of this relationship is suspect due to the formation of a localized plastic zone at the crack tip, in metals. When the plastic zone size remains small compared to the length of the crack the LEFM model gives practically acceptable results, especially if a small "correction factor" is introduced to account for crack-tip plasticity. However, when the material properties, section size, loading conditions and environmental effect combine to produce a large plastic zone the concepts of of LEFM are violated, and "elastic-plastic fracture mechanics" must be employed. This phase of research is in the development stage. Standard testing procedures for fracture toughness testing in the range where LEFM is valid are given in BS 5447:1977.

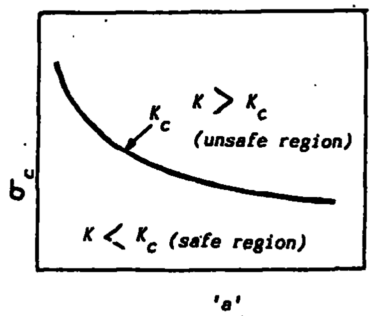

Fig. 3 Variation of σ_c (critical nominal stress) with 'a' (crack length) for rapid crack propergation.

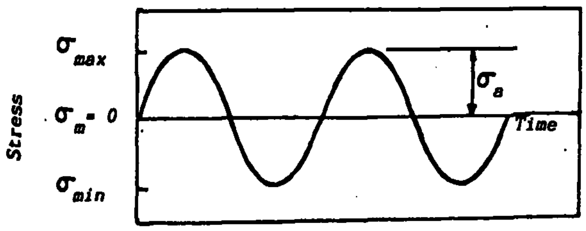

Fig. 4 Typical stress - time variation used in fatigue testing.

$\sigma_{max} = S, \quad \sigma_{min} = -S$

σ_m = mean stress $= \dfrac{\sigma_{max} + \sigma_{min}}{2} = 0$

σ_a = stress amplitude $= \dfrac{\sigma_{max} - \sigma_{min}}{2} = S$

HARDNESS

A simple, convenient and quick method of obtaining a 'measure' of strength and toughness of metals. Commonly used hardness testing methods are Rockwell, Brinnell, and Vickers which determine hardness numbers R_c and R_B, BHN, and VHN respectively. Usually strength is directly proportional to the hardness number while toughness is inversely proportional. Standard testing procedures of the above methods are given in BS 891 : Part 1 : 1962, BS 240 : Part 1 : 1962, and BS 427 : Part 1 : 1961 respectively.

FATIGUE

When the stress - time variation shown in Fig. 4 is applied to a fatigue specimen, the S-N curves (Fig. 5) represents the number of cycles (N) to complete failure at a stress amplitude (S). Premature fatigue failure occurs when $S \geqslant S^*$ (the fatigue limit) - the case for an infinite life design, or when $S \geqslant S^{**}$ (no fatigue limit) - the case for finite life design (after N* loading cycles). These fatigue strength levels (i.e. S* and S**) are below the elastic limit.

Most fatigue data (S-N curves) are obtained for the case of loading shown in Fig. 4, i.e. $\sigma_m = 0$. Data on the influence of σ_m on the fatigue strength (s* or S**) is limited. Therefore when $\sigma_m \neq 0$, usual method is to use proven empirical relationships. Some relationships are shown in Fig. 6 and may be written as follows:

Goodman's Relationship $\dfrac{\sigma_a}{S^{**}} + \dfrac{\sigma_m}{\sigma_u} = 1,$

Gerber's Relationship $\dfrac{\sigma_a}{S^{**}} + \left(\dfrac{\sigma_m}{\sigma_u}\right)^2 = 1,$ &

Soderberg's Relationship $\dfrac{\sigma_a}{S^{**}} + \dfrac{\sigma_m}{\sigma_y} = 1.$

Fig. 6 shows that the experimental data fall between Gerber's and Goodman's relationships and the latter gives a conservative estimate. Standard testing procedures for fatigue testing are given in BS 3518 : Part 1 : 1962, Part 2:1962, Part 3:1963, Part 4:1963, and Part 5:1966.

When using the fatigue strength as a design criterion, factors which influence fatigue behaviour must be taken into consideration. The factors which specifically apply to fatigue strength are, surface conditions, surface treatments, size effect, stress-time variation, and cumulative damage.

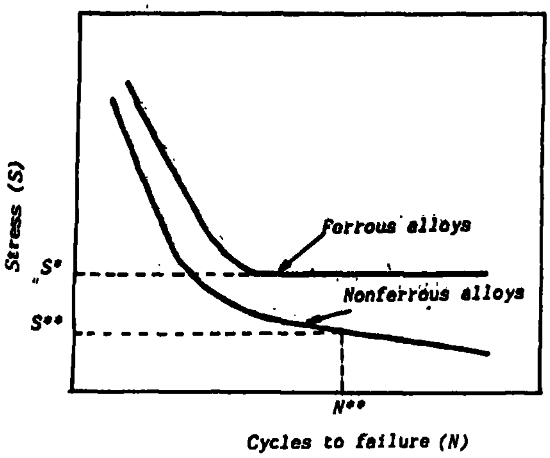

Fig. 5 S-N curves for loading given in Fig. 4. Ferrous alloys show a fatigue limit (S*) while for nonferrous alloys a fatigue strength (S**) after N** cycles (10^7 to 10^8) is selected.

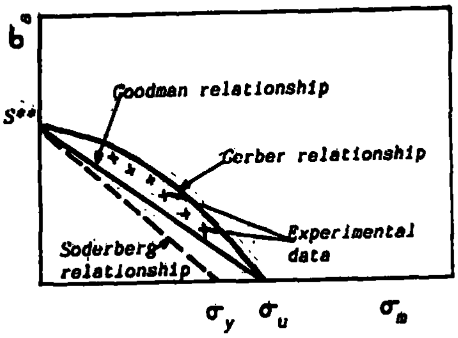

Fig. 6 Illustration of the empirical relationships for estimating the influance of σ_m on σ_a at a fixed fatigue life (N** cycles).
σ_u - tensile strength, σ_y - yield strength.
S** - fatigue strength when $\sigma_m = 0$.

Factors related to metal failure

Other important factors that affect metal failure are given below.

COMBINED STRESS EFFECTS

Designing mechanical or structural components to avoid premature failure is a relatively simple matter if the component is stressed uniaxially. However under complicated loading and geometry conditions three dimensional stress systems act on the component. Therefore in combined stress theories failure is predicted to occur when the maximum value of the selected "parameter" in the multiaxial state of stress becomes equal to or exceeds the value of the same "parameter" that produces failure in a uniaxial stress state. This "parameter" is a stress, strain or energy.

The most useful theories are given below:

(a) Maximum normal stress theory

The "parameter" in this case is the maximum principal (normal) stress. As this is a normal stress, failure is predicted in a brittle mode, and consequently it has been found to be the most suitable failure theory for brittle metals like cast iron.

(b) Maximum Shear Stress Theory

The "parameter" is the maximum shear stress. As this is a shear stress, failure is predicted by a slip process (yielding), and hence has been found to be a suitable failure theory for yielding of ductile metals like steel, aluminium and copper.

(c) Distortion Energy Theory (or Octahedral Shear Stress Theory)

The parameter is the distortion energy/ unit volume. The total strain energy associated with a stress system can be divided into two parts; dilatation energy (due to hydrostatic stress component) and distortion energy (due to shear stress component). Therefore, this "parameter" is associated with slip or shear processes, and is found to be equivalent to the octahedral shear stress theory. Hence as in the maximum shear stress theory, this parameter has been found to be ideal for predicting failure by yielding.

NOTCH EFFECTS

Notches (or Geometric discontinuities) cannot be totally avoided in structural or mechanical components. Screw threads, holes, keyways, fillets are some of the more common cases, while non-intentional geometrics discontinuities may arise due to fabrication processes such as machining and welding. Notches produce complex stress systems which give the following effects;

(1) a non-uniform stress distribution,
(2) A localized triaxial stress system in a uniaxial loading case, and

(3) a stress concentration factor

$$= \frac{\text{actual maximum stress}}{\text{nominal stress}}$$

The ways in which these affect failure are given below:

(1) The effect (2) increases the hydrostatic stress component in the localized region of the notch. This increases the ratio of the maximum principal normal stress/maximum shear stress. This enhances the possibility of failure according to the maximum normal stress theory instead of the maximum shear stress theory. Hence causing brittle fracture in an otherwise ductile metal; similar to the effect of temperature as mentioned earlier in charpy V-note impact testing.

(3) Elastic stress concentration factor or Geometrical stress concentration factory = K_t

K_t has been determined for various geometrical discontinuities under standard loading conditions (eg. axial loading, bending; torsion, etc) using the theory of elasticity and finite element analysis (see Bibliography): When the nominal stress is elastic the localized stress system at the discontinuity can be in the yielding range. The local yielding causes a redistribution of stresses and K_t will decrease to K_p (plastic stress concentration factor). The determination of K_p is very difficult, hence empirical methods have been suggested. for design purposes stress concentration effects have been classified as being either highly local (eg. small holes or fillets; keyways; screw threads) or widely distributed (eg. large fillets; curved hooks, eye-and-clevis joints).

Hence the stress concentration effects may be summarized as in Table 1. The fatigue stress concentration factor K_f may be given by,

$$K_f = \frac{\text{effective fatigue stress}}{\text{nominal fatigue stress}}$$

As in the case of static loading where failure would occur when the actual maximum stress exceeds the failure strength in fatigue; failure would occur when the effective fatigue stress exceeds the fatigue strength. K_f can be related to K_t, by the notch sensitivity index q given by;

$$q = \frac{K_f - 1}{K_t - 1} \qquad (0 \leqslant q \leqslant 1)$$

where;

$$q = \frac{1}{1 + \frac{\rho}{\gamma}}$$

γ- notch root radius; and

ρ- material constant which approaches zero as tensile strength increases. Therefore q approaches unity when the tensile strength of the material is increased.

IMPACT LOADING

Effects of impact loading on components may be separated into two categories;

(1) Produce stresses and strains that are very much larger than the steady values developed under static loading.

(2) Change mechanical properties basically due to increased strain rate. Increases the yield and tensile strengths with a consequent decrease in ductility. The increased yield strength supresses yielding and hence enchances brittle fracture; raises the ductile to brittle fracture transition temperature. Impact loading becomes most critical in this latter aspect when components contains notches.

FABRICATION EFFECTS

Metal fabrication takes place in many forms; machining, cold work welding. They can directly affect failure by their influence on mechanical properties due to effects such as residual stresses; strain age embrittlement; and heat treatment. They can also indirectly affect failure by introducing notches; cracks; microstructural discontinuties and microstructural defects.

ENVIRONMENTAL EFFECTS

The basic mechanical properties of metals discussed earlier were in ambient conditions. However, failure in many cases takes place under different environmental conditions as outlined earlier. These failures generally can be related to the environmental effects on mechanical properties. The major environmental effects on mechanical properties are given below.

(1) Temperature

The basic effects are on strength and ductility; strength increases with a consequent decrease in ductility with decrease in temperature, and vice versa. Due to these basic effects two common modes of failure occur; low temperature embrittlement (eg: - K_c is decreased), and creep at high temperature.The effects of low temperature may be incorporated in design by determining K_c, while when incorporating creep into design only empirical approaches are available. Generally fatigue strength is improved with decrease in temperature and deteriorate with increase in temperature. Combined creep-fatigue is of great importance in high technology designs; eg;- aircraft gas turbines and nuclear power reactors.

(2) Corrosion

Takes place under specific metal-environmental combinations, eg:- aqueous corrosion and gaseous corrosion. The effects on mechanical properties are usually due to the deterioration of the surface fo the component.

These effects may be categorized as follows:

(a) Stress corrosion cracking (SCC) which affect fracture toughness by decreasing K_c to K_{scc}

(b) Hydrogen embrittlement which also decreases fracture toughness

(c) Corrosion - fatigue causes a large decrease in the fatigue strength. Further, in steels it eliminates the fatigue limit.

Design Process

The design process may be carried out in the following sequence.

(1) After examining the design specifications and proposed configuration the "critical" components that may govern the design has to be identified.

(2) The failure mode of these components have to be determined.

(3) Determine the mechanical properties that are directly related to the failure modes. Selection of materials may be done at this stage; cost and availability are important considerations.

(4) Obtain uniaxial strength data of the selected materials in the applicable failure modes. These data may be obtained from available literature, test certificates, or laboratory testing.

(5) Select a safety factor. Premature failure has to be avoided but at the same time materials must be used efficiently. Therefore the margin between operating stress levels and failure strengths must be decided with due regard to the many uncertainities associated with material properties; loading configurations; accuracy of assumed physical and mathematical models relating load, material and failure response. The safety factor can be reduced when these uncertainities are reduced. An average value for the safety factor is about 2.

(6) Calculate the uniaxial design stresses by dividing the uniaxial failure strengths by the safety factor.

(7) Use the applicable combined stress theory of failure to convert the uniaxial design stress to the corresponding design parameter.

(8) Use the design parameter to determine the geometry of the component by an iterative problem - solving and a decision - making process.

Conclusion

Recognition of the potential for metal failure and the identification of the failure modes that persist in the real engineering world are essential when designing to avoid premature failure. There are a wide variety of failure mode in metals that may be encountered. This paper introduces the common failure modes in metals, and the ways they may be incorporated in a quantitative manner to engineering design.

Acknowledgements

The author wishes to thank Dr. M.P. Ranaweera and Mrs. J. Seneviratne of the Faculty of Engineering, University of Peradeniya, for the assistance given in preparation of the manuscript.

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Table I - Effects of Stress Concentration.

Classification of stress concentration	Type of Loading	Type of Metal	Type of Failure	Stress Concentration Factor
Widely distributed	Static	Ductile	Yielding	K_p
Widely distributed	Static	Brittle	Brittle fracture	K_t
Widely distributed	Cyclic	Any	Fatigue fracture	K_f
Highly local	Static	Ductile	Yielding	1
Highly local	Static	Brittle	Brittle fracture	K_t
Highly local	Cyclic	any	Fatigue fracture	K_f