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# Failure of metals and alloys in dentistry

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**Abstract:** Failure of a material is generally to expect the conditions under which a solid material will fail under the action of external loads. The failure of metals is usually classified into ductile failure (yielding) or brittle failure (fracture). Metals can fail in a ductile or brittle manner or both dependent on the conditions such as temperature, type of stress, loading rate. Fracture is the separation of a body into two or more pieces in response to a stress that is static and at temperatures that are low relative to the melting temperature of the materia. In metals, there are two possible fracture modes, ductile and brittle. Fatigue failure occurs in structures subjected to dynamic and fluctuating stresses. Failure occurs at a stress level lower than the yield strength of the specimen. The term fatigue is used because this type of failure normally occurs after a long period of repeated stresses or strain cycling. Fatigue is estimated to be involved in approximately 90% of all metallic failures. Creep is a time-dependent permanent deformation of materials that are used at temperatures that are close to their melting points. creep is normally an undesirable phenomenon. for metals, it becomes important only for temperatures greater than about 0.4 of the melting temperature. In this article different types of metal failure will be discussed showing different mechanics, mechanisms and stages for fracture types, fatigue and creep..

**Keywords:** Failure; metals; alloys.

## Introduction

### 1) Mechanical failure

Failure of a material is generally to expect the conditions under which a solid material will fail under the action of external loads. The failure of metals is usually classified into ductile failure (yielding) or brittle failure (fracture). Metals can fail in a ductile or brittle manner or both dependent on the conditions (such as temperature, type of stress, loading rate) [1, 2].

### a. Fracture

Fracture is “the separation of a body into two or more pieces in response to a stress that is static (constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material”. In metals, there are two possible fracture modes: (ductile and brittle). According to the ability of a material to experience plastic deformation, ductile metals show considerable plastic deformation with high energy absorption before fracture. While in brittle fracture, there is little or no plastic deformation with low energy absorption [1,2].

Any fracture mechanism involves two steps crack formation and propagation in response to an imposed stress. The mode of fracture is highly dependent on the mechanism of crack propagation.

### a.1. Brittle fracture

### Brittle fracture mechanics (Stress concentration)

Fracture mechanics "is the field of mechanics concerned with the study of the propagation of cracks in materials". It calculates the driving force on a crack to characterize the material's resistance to fracture [3]. The measured fracture strengths for most materials are lower than those expected by theoretical calculations based on atomic bonding energies. This discrepancy is due to the presence of microscopic cracks or flows (stress raisers) that exist at the surface and in the interior of a material. These flaws affect the fracture strength because an applied stress may be concentrated and amplified at the tip. Stress amplification also may occur at macroscopic internal discontinuities as voids or inclusions, sharp corners, scratches, and notches [2, 3].

According to Griffith energy balance theory, there are two conditions necessary for crack growth: i. The bonds at the crack tip must be stressed to the point of failure. The stress at the crack tip depends on the ratio of its radius of curvature to its length. ii. The amount of strain energy released must be greater than or equal to that required for the surface energy of the two new crack faces [4].

The degree of amplification of stress depends on:

- Crack length
- Radius of curvature of the crack tip.

The maximum tensile stress could be calculated from this equation [2, 4]:

Where, $\sigma m$ = maximum tensile stress.

$\sigma 0$ = magnitude of the applied tensile stress.

$\rho t$ = radius of curvature of the crack tip.

$a$ = the length of the surface crack or half of the length of the internal crack.

Therefore, for brittle fracture, cracks propagate very rapid, with very little associated plastic deformation. These cracks are unstable, and the crack continues propagation even without an increase in magnitude of the applied stress [2].

### Mechanism of brittle fracture

For the majority of brittle crystalline materials, crack propagation is due to the sequential and repeated breaking of atomic bonds along specific crystallographic planes this process is known as cleavage. Cleavage fracture may be trans-granular or intergranular

i. Trans-granular cleavage [2, 6]:

The cracks pass through the grains, as the cleavage follows a well-defined crystallographic plane.

Microscopically, the fracture surface may have a grainy or faceted appearance due to the changes in orientation from one grain to the other.

**ii. Inter-granular cleavage [2, 6, 7]:**

In some alloys, crack propagation occurs along the grain boundaries known as intergranular fracture, fig. (3a). Inter-granular fractures usually happen after the occurrence of any process that weaken or embrittle grain boundary regions such as overheating of alloys. This weakening of the grain boundary is due to (1) attraction of impurities to grain boundaries which embrittle them, (2) growth of carbide diameter at grain boundaries or (3) environmentally assisted cracking at the grain boundaries.

Microscopically, scanning electron micrographs show the three-dimensional nature of the grains "rock candy appearance" which indicates inter-granular fractur.

### Macroscopic features of brittle fracture surface [2]

Fracture surfaces of brittle materials have flat fractured surface without any signs of plastic deformation (necking) with grainy or faceted shiny texture, fig. (4b). V-shaped "chevron" markings form near the centre of the fracture cross section that indicate the site of crack initiation, fig. (4a).

Brittle fracture surfaces also contain lines or ridges that radiate from the origin of the crack in a fanlike pattern, fig. (5). Usually, these markings are coarse enough to be observed with the naked eye. While, in very hard and fine-grained metals, there is no visible fracture pattern can be observed.

### a.2. Ductile fracture

### Ductile fracture mechanics (Stress redistribution)

Unlike the behaviour around the crack in a brittle material, stresses are redistributed around the crack tip in ductile materials. Deformation occurs at the sharp crack tip results in blunting into a rounded groove. This occurs by sliding of rows of atoms past one another along the slip plane, where the bonds break one at a time and reform immediately with the adjacent atoms [9].

Therefore, ductile fracture is characterised by large plastic deformation in a propagating crack. Moreover, the procedure proceeds slowly as the crack length increases. Such a crack is often stable as it resists any additional crack propagation unless the applied stress increased [2].

### Stages of Ductile fracture

First, after the necking begins, micro-voids are formed in the interior of the cross section. Then, as deformation continues, the micro-voids enlarge and coalesce to form an elliptical crack. The crack continues to grow in a direction perpendicular to the applied stress. Finally, fracture succeeds by the rapid propagation of a crack [2].

### Macroscopic features of ductile fracture surface [2, 5]

In ductile materials, there are two macroscopic fracture profiles. First, for extremely soft metals (as pure gold), these highly ductile materials neck down to a point fracture, showing 100% reduction in area,. Second, for most ductile metals, where fracture is preceded by a moderate amount of necking.

Sometimes, ductile fracture has macroscopic features on the fractures surface termed a cup-and-cone fracture, where one of the surfaces is in the form of a cup and the other surface is like a cone.

Also, in ductile fractured surface the central interior region of the surface has fibrous, irregular and dull look, which indicates the occurrence of plastic deformation.

### Microscopic features of ductile fracture surface [2, 5]

Microscopic examination, using scanning electron microscope (SEM), reveals more details regarding the ductile fracture mechanism. Studies of this type are termed fractographic studies. The scanning electron microscope is preferred over optical microscope for fractographic assessments due to its better resolution and depth of field.

The examination of the fibrous central region in a cup and cone fracture surface with SEM showed numerous spherical dimples which result from uniaxial tensile failure, fig. (10a). Each dimple is a one half of a micro-void that formed and then separated during the fracture process. Dimples can also be formed by shear loading on the 45°lip of the cup and cone fracture, where these dimples will be elongated or C-shaped (parabolic shape dimples), fig. (10b).

Ductile fracture is preferred to brittle fracture because, brittle fracture occurs suddenly and catastrophically without any warning (due to rapid crack propagation). While, in ductile fracture, the plastic deformation gives warning that the material will fail, so that, preventive measures can be considered. Also, more strain energy is needed to produce ductile fracture (because ductile materials are tougher) [2].

### a.3. Ductile to brittle transition in metals

The ductile-brittle transition temperature (DBTT), nil ductility temperature (NDT), or nil ductility transition temperature is "the temperature above which a material is ductile and below which it is brittle". Both ductile and brittle behaviours are dependent not only on the material but also on the temperature (ductile-brittle transition) of the material.

Many steels exhibit ductile fracture at elevated temperatures and brittle fracture at low temperatures. These materials should be used only at temperatures above the transition temperature, to avoid brittle and catastrophic failure [8]. The ductile to brittle transition behaviour is normally found in low carbon steels. Yet, some metals do not go through a ductile to brittle transition, such as low-strength aluminium and copper alloys which remain ductile with decreasing temperature. On the other hand, high-strength steels and titanium alloys maintain a brittle even with increasing the temperature [2]. DBTT is not constant but varies according to previous mechanical and heat treatment, grain size and the nature and amounts of impurities. It can be determined by the amount of impact energy absorption through Charpy or Izod tests [2, 8].

## Fatigue failure

### 1. Dynamic fatigue failure

Fatigue failure occurs in structures subjected to dynamic and fluctuating stresses. Failure occurs at a stress level lower than the yield strength of the specimen. The term fatigue is used because this type of failure normally occurs after a long period of repeated stresses or strain cycling. Fatigue is estimated to be involved in approximately 90% of all metallic failures. Fatigue is catastrophic in nature that occurs without warning. [2]

Fatigue failure process occurs by the initiation and propagation of cracks. The fractured surface is perpendicular to the direction of an applied tensile stress.

The applied stress may be axial (tension–compression), flexural (bending), or torsional (twisting) in nature.

### Types of stress–time modes [9]

Reversed stress cycle: the amplitude is symmetrical about a mean zero stress level. Ie., alternating from a maximum tensile stress ($s_{max}$) to a minimum compressive stress ($s_{min}$) of equal magnitude.

Repeated stress cycle: the maximum and minimum tensile stresses are asymmetrical relative to the zero-stress level.

Random stress cycle: the stress level varies randomly in amplitude and frequency.

From the stress time cure we can determine different parameters that are used to characterize the stress cycle:

- Stress range: the difference between the max. stress and the min. stress.
- Stress amplitude: half the range of stress.
- Stress ratio: the ratio of minimum and maximum stress amplitudes.
- Mean stress: (min stress + max stress)/2

## The S–N curve

The fatigue properties of a material could be determined by laboratory simulation tests. In which the specimen is subjected to cyclic stresses of relatively high max. stress (2/3 tensile strength) & number of cycles till failure is counted. Repeating this procedure on different specimens with decreasing the max stress level progressively. Data are plotted as stress (max stress or stress amplitude) versus logarithm of the number of cycles.[2]

Three parameters could be determined from this curve; fatigue limit, fatigue strength and fatigue life. Where, fatigue limit (endurance limit) is the limit below which fatigue failure will not occur. Some ferrous and titanium alloys show fatigue limit. For many steels, fatigue limits range between 35% and 60% of the tensile strength. While, most nonferrous alloys as aluminum & copper do not have a fatigue limit, so the S–N curve continues its downward trend with increasing N values. Thus, fatigue ultimately occurs regardless of the magnitude of the stress is. For these materials, the fatigue response is specified as fatigue strength.[2]

Fatigue strength is the stress level at which failure will occur for some specified number of cycles.

Another important parameter that is used to characterize fatigue behaviour is fatigue life (*Nf*). It is the number of cycles that causes failure at a specified stress level. Curves for the titanium, magnesium, steel alloys and cast iron display fatigue limits. While curves for the brass and aluminum alloys do not have such limits.

Low-cycle fatigue: is associated with relatively high loads that produce not only elastic strain but also some plastic strain during each cycle. Consequently, fatigue lives are relatively short, and occurs at less than about 104 to 105 cycles.

High-cycle fatigue: for lower stress levels wherein deformations are totally elastic, longer lives result. High-cycle fatigue is required large numbers of cycles to produce fatigue failure, fatigue lives are greater than about 104 to 105 cycles.

### Stages of fatigue failure

The process of fatigue failure is characterized by three definite steps; crack initiation, in which a small crack forms at point of high stress concentration, followed by crack propagation, during which this crack advances incrementally with each stress cycle; and then final failure, which occurs very rapidly once the advancing crack has reached a critical size and the remaining material can no longer withstand the applied forces.[2]

**First stage: Crack initiation**
Crack nucleation sites include pre-existing surface scratches, sharp corners, and indentations. Or cyclic loading can produce microscopic surface discontinuities. Initiation of a new crack in smooth polished metals under cyclic load is caused by irreversible dislocation movement leading to intrusions and extrusions.[9]

**Second stage: Crack propagation**

The mechanism of crack propagation is explained by Plastic blunting and reshaping model:[9]

When reversed stress cycles are applied to a material with a present crack. When tensile loads are applied. At the crack tip, stress is concentrated in the slip zones along the plane of maximum shear stresses (45° to the crack plane) leading to plastic deformation at the tip. When load increases the slip zones at the tip broadens and tip blunting occurs.

When stress is reversed from tension to compression the crack tip sharpens once more by buckling and folding of the newly formed surface into a double notch resulting in striation formation.

Cause of striation formation: when crack closure occurs during compression, it cannot fully wipe out the blunting and the extension of the crack that happened during the preceding tension load, thus, net crack growth occurs during a fatigue cycle, leading to the formation of a striation. Where the distance between two striations is equal to the crack length increment.

**Third stage: Final failure**

When the crack size increases reaching a critical size, the remaining intact material can no longer withstand the maximum applied stress in a loading cycle. Unstable crack growth occurs leading to fracture.

R curve: describes how the material's resistance to crack propagation increases as the crack propagates. In ductile materials this occurs because plastic deformation dissipates energy which works to arrest a growing crack.[9]

Hysteresis Energy: during cyclic loading part of the applied energy is dissipated in the form of plastic deformation (slip at the crack tip) leading to an increase in the resistance to crack growth or what is called cyclic hardening. [9]

**Fractography of fatigue surface**

The region of a fracture surface that formed during the crack propagation step may be characterized by two types of markings termed beachmarks (clamshell) and striations. Both features indicate the position of the crack tip at some point in time and appear as concentric ridges that expand away from the crack initiation site(s), frequently in a circular or semi-circular pattern. Beachmarks are of macroscopic dimensions and may be observed with the unaided eye.

These markings are found for components that experienced interruptions during the crack propagation stage. Each beachmark band represents a period of time over which crack growth occurred. However, fatigue striations are microscopic in size and subject to observation with the electron microscope (either TEM or SEM). Each striation is thought to represent the advance distance of a crack during a single load cycle. Striation width depends on, and increases with, increasing stress range.

**Factors affecting fatigue life**

**Mean stress level:** By increasing the mean stress level, a decrease in fatigue life occurs.

**Geometric design:** It has a significant influence on fatigue behavior. Any notch or geometrical discontinuity can act as a stress raiser and initiation site. The sharper the discontinuity (i.e., the smaller the radius of curvature), the more severe the stress concentration is. The probability of fatigue failure may be reduced by avoiding these structural irregularities or by making design modifications by which sharp corners are eliminated.

**Surface treatments:** during machining operations, small scratches and grooves are inevitably introduced into the surface. This can limit the fatigue life. It has been observed that improving the surface finish by polishing enhances fatigue life significantly.

One of the most effective methods of increasing fatigue performance is by imposing residual compressive stresses within a thin outer surface layer. Thus, a surface tensile stress of external origin is partially nullified and reduced in magnitude by the residual compressive stress. Therefore, fatigue failure is reduced.

In shot peening residual compressive stresses are introduced into ductile metals mechanically by localized plastic deformation within the outer surface region. Small, hard particles (shot) having diameters within the range of 0.1 to 1.0 mm are projected at high velocities onto the surface to be treated. The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter. This results in an improvement in the fatigue properties.

In case hardening a technique by which both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a carburizing or nitriding process. Steel alloy is exposed to a carbonaceous or nitrogenous atmosphere at an elevated temperature. A carbon or nitrogen rich outer surface layer (case) is formed by atomic diffusion from the gaseous phase. The improvement of fatigue properties results from increased hardness within the case and the desired residual compressive stresses which were induced by curburizing or nitriding process.[2]

**Environmental factors** may also affect the fatigue behavior of materials. as thermal fatigue and corrosion fatigue.

Thermal fatigue[2,14] is normally induced by fluctuating thermal stresses and mechanical stresses from an external source that should not be present. The origin of these thermal stresses is the restraint to the dimensional expansion / contraction that would normally occur in the material with variations in temperature. As a consequence of the thermally induced stresses and strains, fatigue may eventually occur. Moreover, Chemical effects of temperature as oxidation must also be considered.

The magnitude of a thermal stresses developed by a temperature change depends on the coefficient of thermal expansion and the modulus of elasticity. Which can be presented by the following equation.

Corrosion fatigue is type of failure that occurs by the synchronized action of cyclic stresses and chemical attack. Corrosive environments have a destructive influence and produce shorter fatigue lives. Even normal ambient atmosphere affects the fatigue behavior of some materials. Small pits may form as a result of chemical reactions between the environment and the material, which may serve as points of stress concentration and therefore act as crack nucleation sites. In addition, the crack propagation rate is enhanced as a result of the corrosive environment.

Several approaches to prevent corrosion fatigue exist. As, protective surface coatings application, selection of a more corrosion resistant material, reduction of the corrosiveness of the environment, reduction of the applied tensile stress level and impose residual compressive stresses on the surface of the member. [14]

**Microstructural variables** affect fatigue life greatly. It was found that the size of the grain affects the critical threshold stress that is required for crack propagation. By decreasing the size of the grain, grain boundaries increase which provide the extended topological obstacles to the slip movement. Moreover, the presence of impurities within the metal increases the obstacles to slip movement and raised the critical threshold stress that is required for crack propagation, thus increasing the number of cycles required to reach the crack critical size and increases the fatigue life.[15]

## 2. Static fatigue

## 3. Creep

Creep is a time-dependent permanent deformation of materials that are used at temperatures that are close to their melting points. creep is normally an undesirable phenomenon. for metals, it becomes important only for temperatures greater than about 0.4 of the melting temperature. [10]

Testing of creep is done by subjecting a specimen to a constant load while maintaining the temperature constant. Then deformation is measured and plotted versus time. In typical creep behavior of metals, upon application of the load, there is an instantaneous deformation, that is totally elastic. The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.

Primary or transient creep, characterized by a continuously decreasing creep rate, the slope of the curve decreases with time. This suggests that the material is experiencing an increase in creep resistance or strain hardening thus deformation becomes more difficult as the material is strained.

Secondary creep, steady-state creep, characterized by constant creep rate thus the plot becomes linear. This is the stage of creep that has the longest duration. The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery. Where, recovery is the process by which a material becomes softer and retains its ability to experience deformation.

Tertiary creep, there is an acceleration of the creep rate and ultimate failure. This failure is frequently termed *rupture* and results from microstructural changes as grain boundary separation, and the formation of internal cracks, cavities, and voids.

The most important parameter from a creep test is steady-state creep rate stage. Through this stage we can determine whether this material is suitable for long or short life applications. In case of short time applications time to rupture, or the rupture lifetime is the main design consideration. For its determination, creep tests must be conducted to the point of failure; these are termed creep rupture tests.

## Factors affecting Creep of Metals

Temperature & stress both influence the creep of metals, effect of creep becomes noticeable when temperature is nearly 0.4 of the melting temperature. With either increasing stress or temperature, the following will be noted:

The instantaneous strain at the time of stress application increases
The steady-state creep rate increases
The rupture lifetime decreases.

In contrast to the influence of grain size on the mechanical behavior at low temperatures as it increases strength and toughness by hindering the dislocation movement. At higher temperature smaller grains permit more grain boundary sliding and diffusional creep, resulting in higher creep rates.

## Mechanism of creep in metals

Depending on the temperature range and the stress level, different mechanisms are involved in the creep process. Diffusion, dislocation climb or glide, or grain boundary sliding can contribute to the creep of metals.

## Diffusional creep [11]

Diffusion mechanism includes passive movement of atoms from high concentration to low concentration till equilibrium. Diffusional creep occurs at a relatively higher temperature and lower stresses compared to dislocation creep.

Nabarro and Herring mechanism

When a low tensile stress is applied on metal at high temperature, vacancies diffuse from grain boundaries that are under tensile stress towards grain boundaries under compressive stress. Diffusion passes through the grain itself. The atoms have slower jump frequencies but more pathways. The atomic diffusion leads to elongation of each grain in the tensile direction.

## Coble mechanism

Based on diffusion of atoms in the grain boundaries instead of in the bulk.

In Coble creep the atoms diffuse along grain boundaries to elongate the grains along the stress axis. This causes Coble creep to have stronger grain size dependence than Nabarro–Herring creep, thus, Coble creep will be more important in materials composed of very fine grains.[19]

Generally, the diffusional creep rate should be the sum of Nabarro–Herring creep rate and Coble creep rate. Diffusional creep leads to grain-boundary separation, by formation of voids or cracks between the grains. To heal this, grain-boundary sliding occurs. The diffusional creep rate and the grain boundary sliding rate must be balanced if there are no voids or cracks remain. When grain-boundary sliding couldn't accommodate the incompatibility, grain-boundary voids are generated, which is related to the initiation of creep fracture.[19]

The strong sensitivity of Coble creep and Nabarro–Herring creep to grain size suggests that larger grain sizes are needed to improve the resistance to diffusional creep.

## Dislocation creep[12]

Dislocation creep occurs at lower temperature and higher stresses when compared to diffusional creep.

## Dislocation slip

Dislocation slip occurs along slip lines and planes at lower temperature when compared to diffusional mechanism. This is the same deformation mode as in conventional deformation at ambient temperature, and it does not depend on diffusion.

## Dislocation Climb

When the applied stress is not enough for a moving dislocation to overcome the obstacle on its way via dislocation slip alone, the dislocation could climb to a parallel slip plane by diffusional processes, and the dislocation can glide on the new plane. This process repeats itself each time when the dislocation encounters an obstacle.

In which atoms move out of the slip plane. Higher temperatures than that required for dislocation slip and lower stress permit dislocations in a metallic material to climb. The dislocation climb occurs to bypass obstacle present in the same plane. These obstacles could be created by the pileup effect of multiple dislocations that increases the resistance to dislocation movement. Thus, further dislocations cant occur within this plane. Incase of elevated temperatures the increased energy permits dislocations to climb to a different plane. [18]

## 3. Grain-Boundary Sliding [16]

It is important to discuss the importance of grain boundary sliding phenomena. These are needed to prevent micro-void or microcrack formation due to the mass transfer associated with grain boundary or bulk diffusion. Hence, the diffusion creep rates must be balanced exactly by grain boundary sliding rates to avoid the opening up cracks or voids.

Note that the grain boundary sliding heals the crack/voids that would otherwise open up due to grain boundary diffusion. The sliding of the grain boundaries (due to an applied shear stress) must be coupled with diffusional accommodation to avoid opening up of cracks or microvoids. Diffusional creep and grain boundary sliding are, therefore, sequential processes. As with most sequential creep processes, the slower of the two processes will control the creep rate. However, large amounts of such sliding may lead, ultimately, to microvoid nucleation and creep rupture in the tertiary creep regime.

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