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Review article

Fatigue in dentistry: a review

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Abstract: Dental materials are subjected to complex stresses in the oral cavity over a long period during function. Therefore, it's important to understand how dental materials function and the types of failure inside the patient mouth. Fatigue may result in microcrack formation and eventually failure.

Keywords: *Fatigue, Fatigue in dentistry, Fatigue mechanism*

Introduction:

Fatigue is a form of failure that occurs within structures subjected to dynamic and fluctuating stresses. It is possible to occur at a stress level below the yield strength. This type of failure occurs after a period of repeated stress or strain cycle. Fatigue is catastrophic and occurring suddenly.[1]

Tensile, compressive, and shear stresses can all lead to fatigue failure. Fatigue failure is like a brittle failure in nature that there is little plastic deformation with the failure. Failure occurs by crack initiation, and propagation.[2]

Different modes of stress cycles

Three different stress-time modes are possible.

1) Reversed stress cycle

It is regular, sinusoidal time dependence, where the maximum and the minimum stresses are equal. The material is loaded in tension (positive stress), and compression (Negative stress) within a cycle.[3]The amplitude is symmetrical around zero stress level, alternating with a maximum tensile and minimum tensile stress of equal magnitude.[1] (Figure 1)

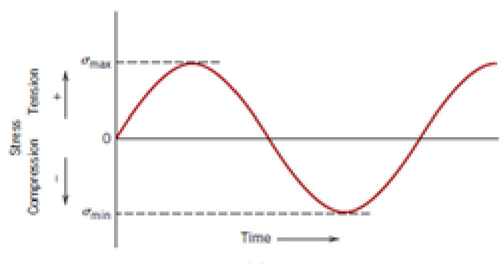


Figure 1: Reversed stress cycle

2) Repeated stress cycle

It is the stress cycle where the maximum and the minimum stresses are asymmetrical around zero stress level.[1] (Figure 2)

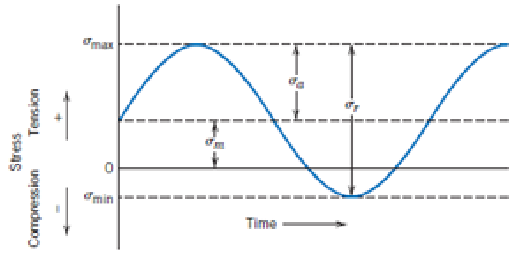


Figure 2: Repeated stress cycle

3) Random stress cycle

The stress level is subjected to random loads in amplitude or frequency. (Figure 3)

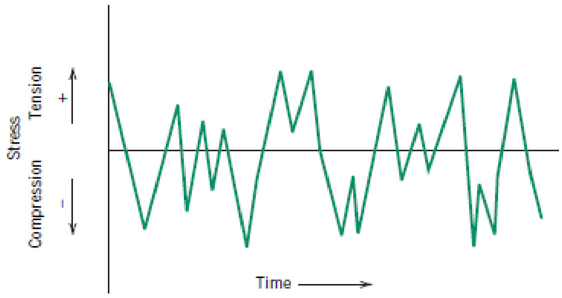


Figure 3: Random stress cycle

Most common type occurring in the oral cavity is the reversed cycle[3]

- Tensile stresses are positive, and compressive stresses are negative.
- There are several parameters used to describe the fluctuating cycle:

Mean stress σ_m: is the average of the maximum and minimum stresses in the cycle

$$\sigma_m = \frac{\sigma max + \sigma min}{2}$$

Range of stress σ_r: is the difference between σ_{max} and σ_{min}

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress amplitude σ_a: is half the range of stress

$$\sigma_a = \frac{\sigma max - \sigma min}{2} = \frac{\sigma r}{2}$$

- Stress ratio(R): is the ratio between the minimum and the maximum stress[1]

$$R = \frac{\sigma min}{\sigma max}$$

Mechanism of failure

Generally, the process of fatigue failure includes:

- **Crack initiation**: where small crack forms at some point of high concentration.
- **Crack propagation**: where crack advances with each stress cycle.

- **Final failure**: occurs rapidly once the crack reached a critical size.

During fatigue failure, cracks are initiated on the surface at the point of stress concentration. Crack sites are surface scratches, keyways, threads, and dents. Cyclic loading can produce microscopic surface discontinuities from dislocation slips that may act as stress raisers and crack initiation sites.[1]

Mechanism of failure among the different materials

1) Polymer:

Fatigue is a common reason for mechanical failure of polymers. Crack propagates in the material when cyclic load on the material reaches a critical value leading to fatigue failure.[4] Polymer fatigue is sensitive to environment (temperature), molecular weight, molecular density and aging. In polymer matrix, fatigue resistance increases as crystallinity increase. During fatigue, there is change in van der Waal force that results in the movement of the polymer chains and creating unfolding of the polymer chains. [5]

The contact between the polymer and the sliding counter-face results in increasing the mobility of the macromolecule chains, and this increases the irreversible shift of the macromolecule chains due to the contact stresses. As the number of the intermolecular bond breakage increases, microdefects appear in polymers. During friction microdefects accumulate resulting in the appearance of microcracks.[6, 7]

2) Ceramics:

Cyclic fatigue in ceramics refers to fatigue crack propagation. It is a rate dependent crack growth in the presence of moisture. As water enters the fissures and break down the cohesive bonds within the material forming what is called Subcritical or slow crack growth which progress over time, accelerating at higher stress levels and leading to failure. The good fabrication procedures and avoiding of the surface damage is critical in the prosthetic dentistry to avoid the failure process.[8] Water can enter the crack tip and accelerate the chemical corrosion attack in ceramics especially silicate base, by breaking the primary chemical bonds of ceramics at the crack tip causing subcritical propagation until the crack reached critical crack size for failure, and hydrolyzing the siloxane bonds even at moisture level as low as 0.02%.

3) Metals:

For metals, fatigue is expressed in the form of irreversible motion of dislocation and their interactions. The primary mechanism of fatigue in metals is the localization of strain as first step in crack initiation. Strain accumulates through dislocation resulting in slip. Slip moves until it is irreversible. In many metals, the strain is localized in the form of slip bands. The accumulation of slips during cyclic loadings, leads to plastic deformation and the nucleation of micro-cracks. The lifetime of metal depends on the amount of cycles needed to initiate a crack and the amount of cycles required to propagate the crack to the failure point.[9, 10]

4) Composite

In resin composite, many mechanisms participate in fatigue damage of composite, including matrix degradation, void formation, filler debonding and filler failure. Fatigue fracture occurs from internal or external micro-flow, from which crack propagates and leads to fracture.[6] Crack growth in composite is related to the composition, microstructure and susceptibility to degradation. Water exposure will lead to weakening of resin composite, so this accelerates the crack growth. As the microstructure affect the fatigue resistance; high filler loaded materials and small filler particles are more fatigue resistant.[11]

Microscopic and Macroscopic Features of fatigue

The region of the crack formed during crack propagation is characterized by one of two types of markings**: beach-marks and striation**.

Concentric ridges expand from the crack initiation sites in a circular or semicircular pattern. Beach-marks are a macroscopic feature and are also called clamshell marks. They are formed when the material experiences interruption during the crack propagation stage. Beach-marks indicate a change in growth rates when fatigue is applied in a consistent number of cycles. Each beach-mark represents a period of time where crack growth occurred. Each package produces a total crack extension than can be seen without enlargement. Packages of load repetition may be shorter or longer than periods of rest. Each beach-mark is a single or more packages of cycles, not a single cycle and it is a progressive stage of crack propagation. [1] (Figure 4)

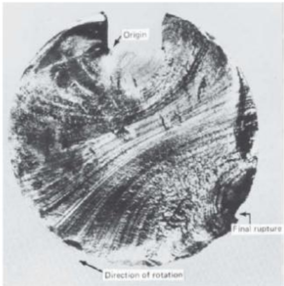


Figure 4: Detected beachmark in fatigued material

Striation is microscopic in size and can be observed by using scanning electron microscope or transmission electron microscope. Each striation represents a single cycle. It is the advanced distance of a crack during a single load cycle. Striation depth increases with increasing the stress range. During propagation of fatigue cracks and on a microscopic level, there is localized plastic deformation at crack tips even though the maximum stress to which the object is exposed is below the yield strength of the metal. The applied stress is amplified at the crack tip so that the local stress exceeds the yield strength of the metal.[1] (Figure 5)

Figure 5: Striations observed in fatigued material

Although beach-marks and striations are fatigue surface features having a similar appearance, they come from different origins and sizes. There may be thousands of striations in a single beach-marks.

The presence of beach-marks and striations confirms that the cause of failure was fatigue, but the absence of either or both doesn't exclude fatigue. The appearance of striations may depend on the stress state. Detection of striation decreases with time because of the formation of surface oxide films or corrosion products. Beach-marks and striations don't appear in the region of rapid failure. Rapid failure may be ductile or brittle. [1] (Figure 6)

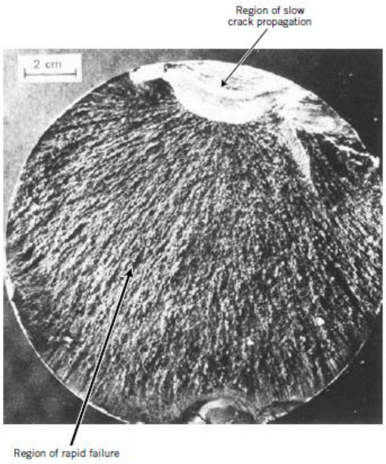


Figure 6: Crack on the top is propagated slowly, while dull and fibrous area is fast

Fatigue testing method

The most common method to test fatigue is the ***rotating-bending beam***.

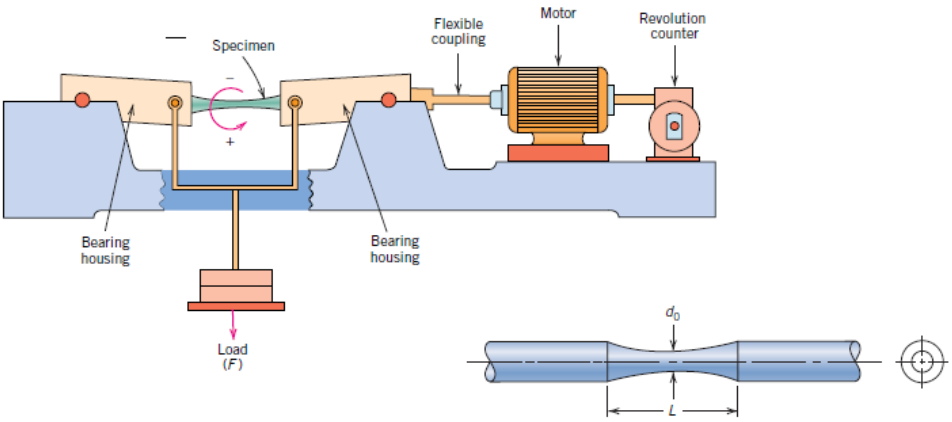


Figure 7: Rotating bending beam

It is alternating tension and compression of equal magnitude on the specimen as it is bent or rotated. In this case, the stress cycle is reversed, so that the stress ratio is -1. The lower surface of the specimen is subjected to tension (+ positive) while the upper part of the specimen is subjected to compression (- negative). (Figure 7)

Series of tests are started by subjecting the specimen to stress cycling at large maximum stress, usually on the sequence of two-thirds of the tensile stress, and then the number of cycles to failure is counted and recorded. The procedure is repeated with decreasing stress levels. Then the data is described on a graph where S is the stress and N is the number of cycles to failure for each specimen (S-N Curve). In the S-N curve, the higher the magnitude, the smaller the number of cycles the material can withstand before failure.[1]

Failure could be tested simulating the actual clinical condition for the various dental restorations.

Types of S-N Curves:

Two types of S-N curves are observed:

1) S-N curve with Fatigue limit:

There is a stress limit level called Fatigue limit or endurance limit. (Figure 8)

Fatigue limit or the endurance limit is the largest stress the material can withstand an infinite number of cycles without failure. Below such value fatigue failure doesn't occur. For many steels, this limit is 35-60% of the tensile strength. E.g. Fatigue for ferrous (Iron-base) and titanium alloys.[1]

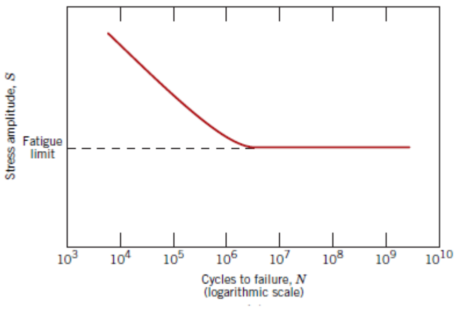


Figure 8: Fatigue limit

2) S-N curve without fatigue limit:

The S-N curve continues downward at a greater number of cycles. Therefore, fatigue occurs regardless of the number of cycles. Fatigue in those alloys is defined as the fatigue strength.

Fatigue strength is the stress level at which failure will occur for a specific number of cycles (10^7).

Fatigue life is the number of cycles that cause failure at a specific stress level. [1](Figure 9) E.g. fatigue for non-ferrous alloys

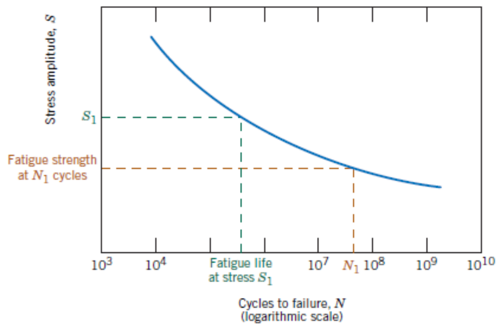


Figure 9: Fatigue life

From the graph below (Figure 10) Cast iron, Mg alloy, and steel have a fatigue limit, while Aluminum alloy, titanium alloy, and brass don't show a fatigue limit.[1]

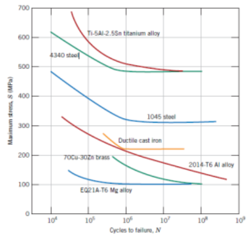


Figure 10: Materials with fatigue limit

Fatigue from the previous S-N curves shows the best-fit curves, while fatigue fails at a stress level 25% below the curve.

Factors affecting fatigue life:

Fatigue is affected by many variables including mean stress level, geometric design, surface effect, metallurgical variables, and environment.

1) Loading condition

a) Mean stress:

Fatigue life depends on stress presented on the S-N. Those data are taken for a constant mean for the reversed cycle, the mean stress is σ. Mean stress also affects the fatigue life. Increasing the mean stress level leads to decreasing the fatigue life.[1] (Figure 12)

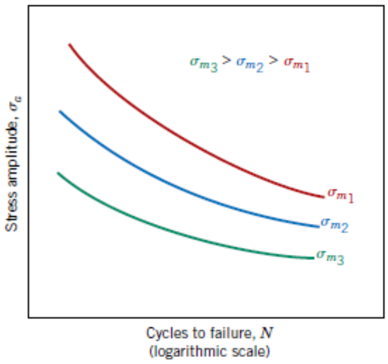


Figure 12: mean stress

b) Number and load of cycles

1) Low cycle fatigue:

If the number of cycles is small, then this is called low cycle fatigue. This is associated with high loads that produce not only elastic strain but also some plastic strain.[1]

2) High cycle fatigue:

If the number of cycles is large, then this is called high cycle fatigue. This is associated with a low stress levels where the deformation is elastic. [1]

1) Specimen condition

a) Surface effect

The maximum stress within a structure occurs at its surface. Most cracks occur at the surface causing stress amplification leading to fatigue. Therefore, fatigue life is sensitive to the surface of the component. Design criteria and surface treatments affect the fatigue resistance, which improves the fatigue life.[1]

b) Surface treatment

During operation, small scratches are introduced to the structure. Those scratches decrease fatigue life. Polishing and improving the surface finish enhances the fatigue life. One of the effective methods to increase the fatigue performance is to introduce residual compressive stresses in the thin outer surface layer. So, the tensile stress of external origin is nullified and reduced by the compressive stress, therefore the net effect is decreasing the crack formation and the fatigue failure.[1]

Residual compressive stresses are induced in ductile metals by localized plastic deformation within the outer surface. This is accomplished by a process called shot peening. Shot peening is a process where small, hard particles having 0.1 to 1.0 mm diameters are projected with high velocities to the surface to be treated. The deformation induces compressive stresses to a depth of one quarter and one half of the shot diameter.[1] (Figure 13)

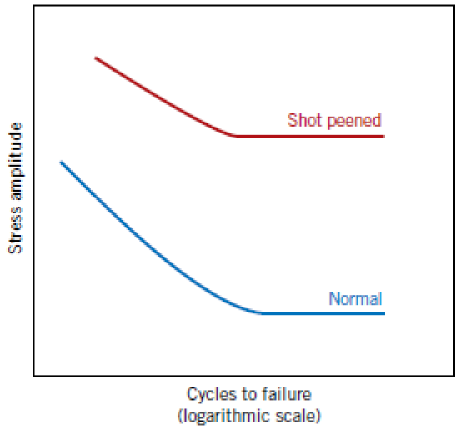
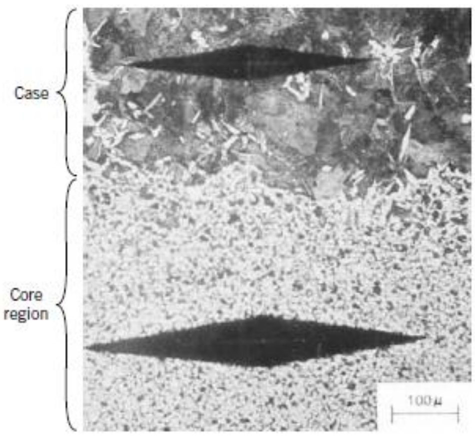


Figure 13: Shot peening effect

Fatigue life for steel is improved by **Case hardening**. This is accomplished by carburizing and nitriding process where exposure to carbon or nitrogen atmosphere at elevated temperature. Therefore, carbon or nitrogen-rich outer layer is introduced by atomic diffusion from the gaseous phase. This layer is 1mm deep and is harder than the core material. This will lead to the improvement of fatigue and increasing the hardness as well as introducing desired residual compressive stresses. As shown in the following figure, the hardness in the outer case is greater than the core [1](Figure 14)

Figure 14: Hardness in the outer case is greater than the core



3) Material

a) Type of material

Fatigue failure differs according to the material from metals, ceramics, composite and polymer.

b) <u>Design factor</u>

The design of the structure influences the fatigue characteristics. Any geometrical discontinuity can act as a stress raiser and crack initiation site. Geometrical discontinuity includes grooves, holes and threads; the more severe the discontinuity the more the stress concentration. Fatigue failure can be reduced by avoiding those geometrical discontinuities, or by making design modifications.[1]

3) Environmental effects:

Environmental factors may affect fatigue behavior; those factors include thermal fatigue and corrosion fatigue.

a) Thermal fatigue:

Thermal fatigue is induced at high temperatures by fluctuating thermal stresses when the mechanical stresses are absent. Thermal stresses are induced due to the restraint to the dimensional expansion and/or contraction that would occur with changing the temperature. The magnitude of thermal stresses developed by temperature change (ΔT) depends on the coefficient of thermal expansion (α) and the modulus of elasticity (E).[1]

$\sigma = \alpha_1 E\Delta T$

Thermal stresses do not rise if the mechanical restraint is absent. So, to reduce this thermal fatigue, this is performed by eliminating the restraint source, so this will allow dimensional changes with temperature changes or choosing a material with appropriate physical properties.[1]

b) Corrosion fatigue:

Corrosion fatigue occurs as a result of simultaneous cyclic stresses and chemical attacks. Corrosive environments produce shorter fatigue lives. Small pits may be formed as a result of a chemical reaction between the environment and the material which may act as a stress concentration point and crack nucleation site.[1]

Corrosive fatigue is caused by the rupture of the material protective passive film. The material become weakened due to cyclic loading, the oxide layer become damaged due to alternating tensions and compression. The loss of the oxide layer invites more corrosion, so lowering the strength of the material and shortening the lifespan.[12]

Lowering the load application leads to exposing the opened crack to the environment for long time, reducing the fatigue life.

CONCLUSION

Dental materials are subjected to fatigue in the oral cavity. Protection of the dental prosthesis is one of the methods to decrease the fatigue from decreasing the normal fatigue failure reasons to selecting corrosion resistant materials and reducing the corrosiveness fo the environment.

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