Bending Fatigue Failure In Gear Tooth

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Abstract

Most materials will fracture when submitted to periodic loads over a large number of cycles. Tooth bending fatigue is one of the most common modes of fatigue failure in gears. It results in progressive damage to gear teeth and ultimately leads to complete failure of the gear. The initial crack is located at the point of the largest stresses in a gear tooth root. The complete bending fatigue failure of mechanical elements is mainly divided into two parts namely ''crack initiation" and ''crack propagation period''. The complete service life of mechanical elements N can then be determined from the number of stress cycles Ni required for fatigue crack initiation and the number of stress cycles Np required for a crack to propagate from the initial to the critical crack length and failure as, N=Ni + Np. Various factors affecting the fatigue strength and methods to improve the fatigue life are discussed.

1. Introduction

A gear is a machine element designed to transmit force and motion from one mechanical unit to another. The design and function of gears are usually closely associated, since gears are designed for a specific function. Like all mechanical components, gears can and do fail in service for a variety of reasons. In most cases, except for an increase in noise level and vibration, total gear failure is often the first and only indication of a problem. The general types of failure modes in gear teeth (in decreasing order of frequency) include fatigue, impact fracture, wear and stress rupture. Of these, one of the most common causes of gear failure is tooth bending fatigue. It results in progressive damage to gear teeth and ultimately leads to the complete failure of the gear.

2. Review of Literature

T. Osman and Ph. Velex had developed the model combining the analysis of crack initiation and propagation in relation to dynamic tooth loads has been presented. The approach is limited to bi-dimensional problems. Dynamic tooth loads are found to be highly influential depending on the speed range since they can induce fatigue damages at certain points on the tooth profile which would not occur at lower speeds [1].

Robert F. Handschuh and Timothy L. Krantz, Bradley A. Lerch, Christopher S. Burke conducted the test using the single-tooth bending method to achieve crack initiation and propagation. Test loads were applied at the highest point of single tooth contact. Gear bending stresses for a given testing load were calculated using a linear-elastic finite element model [2]. P.J.L.Fernandes discussed the characteristics of tooth bending fatigue failure and a number of actual case studies were presented which shows the occurrence of this failure mode in the practice [3].

D. Jelaska, S. Glodež, J. Kramberger, S. Podrug presented the computational model for determination of service life of gears in regard to bending fatigue in a gear tooth root. The fatigue process leading to tooth breakage in a tooth root is divided into crack initiation (Ni) and crack propagation (Np) period, which enables the determination of total service life as N = Ni+Np [4]. Osman done the failure analysis of a helical gear used in gearbox of a bus. An evaluation of the failed helical gear was undertaken to assess its integrity that included a visual examination, photo documentation, chemical analysis, micro-hardness measurement, and metallographic examination. He found that teeth of the helical gear failed by fatigue with a fatigue crack initiation from destructive pitting and spalling region at one end of tooth in the vicinity of the pitch line because of misalignment[5].

3. Causes of Breakage Failure

Fatigue is the most common failure in gearing. Tooth bending fatigue and surface contact fatigue are two of the most common modes of fatigue failure in gears. Several causes of fatigue failure have been identified. These include poor design of the gear set, incorrect assembly or misalignment of the gears, overloads, inadvertent stress raisers or subsurface defects in critical areas, and the use of incorrect materials and heat treatments [6].

3.1. Incorrect Assessment of Load

The load imposed during the operation has not been ascertained properly due to limitations of data available.

3.2. Impact Loads

The impact loads faced by the teeth due to shocks have not been taken into account for load calculations .The impact loads due to shocks may be as a result of characteristics of the drive.

3.3. Incorrect Choice of Material

Incorrect choice of material may occur in some cases due to mix-up of material at production stage wherein gears may be produced of wrong material without the mistake being detected. It could as well be the result of wrong choice of material at design stage by understanding the load. There is disagreement among the gear designers whether the Izod test value can indicate the sensitivity of tooth breakage to impact load. However, tough steel is definitely better than a brittle one. Failure of gear tooth solely due to the use of steel having low Izod value is almost unknown.

3.4. Increased Load due to Mal-distribution of Load

Increased load is faced by gear due to errors in mountings (misalignment of axes), errors in helix angles and errors in manufacture due to distortion, such as heat treatment distortion. Due to this, gear does not have the full length contact as assumed in gear design, but has reduced contact, which increases the load on gear tooth. Maldistribution of load also arises from lack of rigidity in structure supporting the gears.

3.5 Errors in Gear Teeth

Errors in gear teeth change the relative velocity of the mating gear. This causes the momentary acceleration and deceleration of gear train, resulting in force called the dynamic load. The following items cause this load.

1. Tooth errors, such as spacing error, profile error, lead error, and pith line run out.

2. Tooth stiffness variation due to tooth geometry and variation in elasticity of material.

3. Gear inertia, which is dependent on gear mass and pitch-line velocity.

3.6. Stress Risers

Most failures result from excessive tooth load, which result in root stress higher than the endurance limit of the material. Then gears are loaded in this manner and subjected to enough repeated cycles, the gear teeth will fail. Sometimes stress risers, help to aggravate this condition and subject the gear teeth to higher root stress levels than would normally be predicted. Such risers includes notches in root fillets, hob tears, inclusions, small heat-treat cracks, grinding burns and residual stresses.

4. Tooth Bending Fatigue

Surface contact fatigue of gear teeth is one of the most common causes of gear operational failure due to excessive local Hertzian contact fatigue stresses. Generally, there are two types of surface contact fatigue, namely, pitting and spalling. The pitting of gear is characterised by occurrence of small pits on the contact surface. Pitting originates from small, surface or subsurface initial cracks, which grow under repeated contact loading. Pitting is a three-dimensional phenomenon and strongly depends on contact surface finish, material microstructure and operating conditions, such as type of contact, loading, misalignment, lubrication problems, temperature, etc. Spalling, in general, is not considered an initial mode of failure but rather a continuation or propagation of pitting and rolling contact fatigue. Although pitting appears as shallow craters at contact surfaces, spalling appears as deeper cavities at contact surfaces [5].

Gearboxes are generally robust and reliable devices. However, problems do occur particularly due to application error. Application errors can be caused by a number of problems, including mounting and installation, vibration, cooling, lubrication, and maintenance. Misalignment is probably the most common, single cause of failure, Due to misalignment; the pinion does not mesh properly with the gear during operation, and this lead to a high stress concentration at the surface of gears. The misalignment also leads to severe wear and excessive heat generation at the mating surface. In gears, it is exhibited as premature pitting at one end of the tooth. There are many causes of misalignment, both static (manufacturing or setting-up errors) and dynamic, due to elastic deflections of components under load, and also due to thermal expansion. Also, damage to and failures of gears in gearbox can and do occur as a direct or indirect result of lubrication problems [5].

The stresses on a gear tooth can be analyzed by considering the tooth to be a short cantilever beam with the load applied at the bearing surface. This is shown schematically in Figure 1. The maximum tensile stresses occur at the root radius on the active (i.e. loaded) flank of the gear tooth, while the maximum compressive stresses occur at the root radius on the passive flank. A zero-stress point therefore exists below the root circle at or near the tooth centre-line. Depending on the geometry of the gear tooth and the characteristics of loading, the stress concentration at the root radius where maximum tensile stresses are experienced may vary from 1.4 to 2.5. With the cyclic variation in loads characteristic of gear operation, these regions become preferential sites for fatigue crack initiation [3].

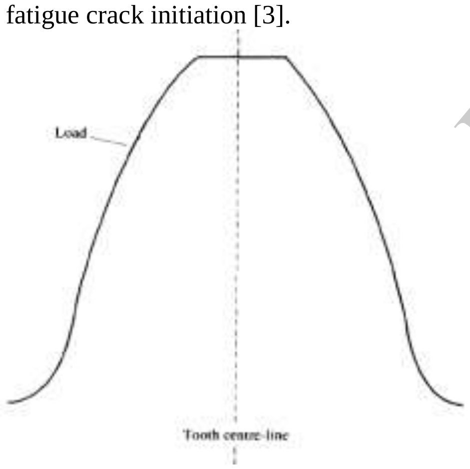

Figure 1. A Gear Tooth as a Small Cantilever Beam

Once a fatigue crack initiates at the root radius, it propagates towards the zero-stress point, which is initially below the root circle near the tooth centre-line .However, as crack propagation proceeds, the zero-stress point is displaced laterally until it reaches a position under the opposite root. At this stage, the shortest untracked section lies between the crack tip and the opposite root, and final crack growth proceeds in this direction. This results in the L-shaped crack paths often observed in practice [3].

As the fatigue crack propagates, the cracked tooth is deflected, thus allowing the adjacent gear teeth to pick up the load. The higher loads on these teeth, in turn, impose higher stresses at the corresponding root radii and lead to further fatigue crack initiation. As a result, tooth bending fatigue usually leads to failure of a number of adjacent gear teeth [3].

Several classical standardized procedures (DIN, AGMA, ISO, etc.) can be used for the approximate determination of load capacity of gear tooth root. They are commonly based on the comparison of the maximum tooth-root stress with the permissible bending stress [1]. Their determination depends on a number of different coefficients that allow for proper consideration of real working conditions (additional internal and external dynamic forces, contact area of engaging gears, gear's material, surface roughness, etc.). The classical procedures are exclusively based on the experimental testing of the reference gears and they consider only the final stage of the fatigue process in the gear tooth root, i.e. the occurrence of final failure.

5. Fatigue Failure Process

However, the complete process of fatigue failure of mechanical elements may be divided into the following stages [4].

(1) Micro crack nucleation;
(2) Short crack growth;
(3) Long crack growth; and
(4) Occurrence of final failure.

In engineering applications the first two stages are usually termed as "crack initiation period", while Long crack growth is termed as "crack propagation period". An exact definition of the transition from initiation to propagation period is usually not possible. However, the crack initiation period generally account for most of the service life, especially in high cycle fatigue, see Figure 2. The total number of stress cycles N can then be determined from the number of stress cycles Ni required for the fatigue crack initiation and the number of stress cycles Np required for a crack to propagate from the initial to the critical crack length, when the final failure can be expected to occur.

$$N = N_i + N_p \qquad (1)$$

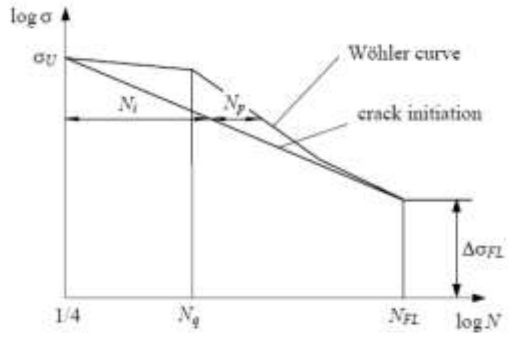

Figure-2.The service life of mechanical elements

6. Fatigue Crack Initiation

The initiation of fatigue cracks represents one of the most important stages in the pitting process. The position and mode of fatigue crack initiation depends on the microstructure of the material, the type of stress and the micro- and macro-geometry of the specimen [1].

The material is often considered as homogenous with no defects such as inclusions, asperities, etc. However, some alter- native approaches are based on the dislocation model of Tanaka and Mura which considers that subsurface cracks initiate from inclusions [4].

Presented model for the fatigue crack initiation is based on Coffin-Manson relation between deformations (ε), stresses (σ) and number of cycles (Ni), which can be described as follows

$$\Delta\varepsilon = \Delta\varepsilon_{el} + \Delta\varepsilon_{pl} = \frac{\sigma'_f}{E} N_i^b + \varepsilon'_f N_i^c \qquad (2)$$

[4].

Where Δε is the strain range, Δεel and Δεpl are the elastic and plastic strain range, E is the Young's modulus of the material and σ'f, ε'f, b and c are the strength coefficient, ductility coefficient, strength exponent and ductility exponent for crack initiation, respectively. The strain range can be obtained numerically (usually by FEM), or by strain gauges measuring the area of tooth root, where the crack initiation is expected. The material constants σ'f, ε'f, b and c are obtained for each material and stress/strain ratio, from strain controlled tests [4].

In the HCF region commonly implicated for gears, where the plastic strain can be neglected, the Coffin-Manson relation reduces only to elastic part and so transforms to an equation of the Basquin type [4].

$$(\Delta\sigma)^{k_i} \cdot N_i = C_i \qquad (3)$$

Where Δσ is the applied stress range and ki and Ci are the material constants. It is easy to obtain the crack initiation life Ni using this relation, if we assume that the crack initiation curve passes the same point (NFL; ΔσFL) as the Wohler curve, it means at the fatigue limit level the whole fatigue

$$N_i = N_{FL} \cdot \left(\frac{\Delta\sigma_{FL}}{\Delta\sigma}\right)^{k_i} \qquad (4)$$

life consists of the crack initiation period [4].

Where NFL is the number of cycles at the knee of the Wohler curve, see Figure 2. On the basis of the same assumption, the exponent ki can be obtained as:

$$k_i = \frac{\log(4N_{FL})}{\log(\sigma_U / \Delta\sigma_{FL})} \qquad (5)$$

Where σU is the ultimate strength, see Figure 2. This relation was found to be in a good correlation with available experimental results. The most important parameter when determining the crack initiation life Ni according to equation (4) is the fatigue limit ΔσFL, which is a typical material parameter and is determined using appropriate test specimen. When determining the fatigue limit for gears, the reference test gears are usually used as the test specimens. According to ISO standard, they are spur gears with normal module mn=3 to 5 mm, tooth width B= 10 to 50 mm, surface roughness Rz≈10 µm, etc, which are loaded with repeated pulsating tooth loading. If geometry, surface roughness, gear size and loading conditions of real gears in the praxis deviate from the reference testing, the previously determined fatigue limit ΔσFL must be modified through the appropriate correlation factors.

Fatigue Damage Indicator (D_f)

The Fatigue Damage Indicator can be defined as the ratio of the equivalent stress (σ_{eq}) to the limiting fatigue stress (σ_{Li}) [1].

$$D_f = (\sigma eq) / (\sigma Li)$$

If Df <1, there is no risk of damage
If Df ≥1, fatigue failure is likely to occur

7. Fatigue Crack Propagation

Crack propagation from the initial fatigue crack (under the surface) to the critical crack length is studied analytically based on the principle of linear elastic fracture mechanics (LEFM) .The application of LEFM to fatigue is based upon the assumption that the fatigue crack growth rate, da/dN, is a function of the stress intensity range $\Delta K = K_{max} - K_{min}$, where a is a crack length and N is a number of load cycles. In this study the simply Paris equation is used to describe of the crack growth rate [1, 4].

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left[\Delta K(a)\right]^m \tag{6}$$

Where C and m are the material parameters

If da/dN = 0, no crack growth,

If da/dN >0, crack propagates

In respect to the crack propagation period Np according to Eq.1, and with integration of Equation 6, one can obtain.

$$\int_0^{N_p} \mathrm{d}N = N_p = \frac{1}{C}\cdot\int_{a_0}^{a_c} \frac{\mathrm{d}a}{\left[\Delta K(a)\right]^m} \tag{7}$$

Material parameters C and m and can be obtained experimentally, usually by means of a three point bending test as to the standard procedure ASTM E 399-80 [4].

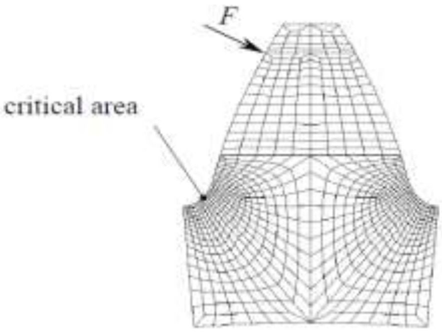

Figure-3. Finite Element Model

The computational procedure is based on incremental crack extensions, where the size of the crack increment is prescribed in advance. In order to predict the crack extension angle the maximum tensile stress criterion (MTS) is used. In this criterion it is proposed that crack propagates from the crack tip in a radial direction in the plane perpendicular to the direction of greatest tension (maximum tangential tensile stress) [4].

The initial crack has been located perpendicularly to the surface at the point of the maximum equivalent stress (calculated after Von Mises) stress on the tensile side of gear tooth [4].

The loading cycles Np for the crack propagation to the critical crack length can then be estimated using equation (7). Figure 4 shows the numerically determined crack propagation path in a gear tooth root [4].

On the basis of the computational results for crack initiation (Ni) and crack propagation (Np) period, the complete service life of gear tooth root can be obtained according to equation (1), see Figure 5. Those computational results for total service life are in a good agreement with the available experimental results, which are taken from [4].

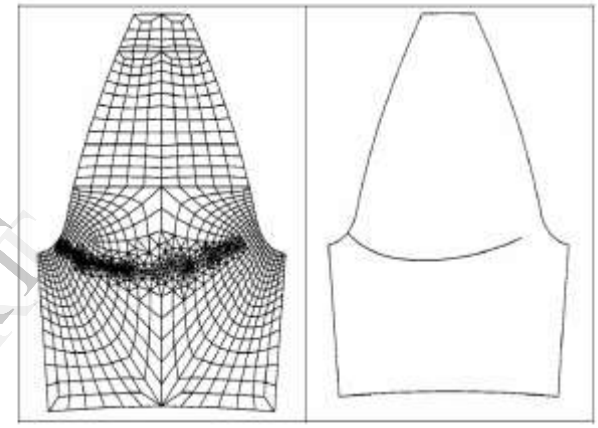

Figure-4. Crack propagation path in a gear tooth root

8. Graph’s of Fatigue Crack Initiation and Propagation

A series of single tooth bending tests have been conducted on AISI 9310 spur gears. Tests were conducted from 1/4 cycle to thousands of cycles. A series of single tooth bending tests have been conducted on AISI 9310 spur gears. Tests were conducted from 1/4 cycle to thousands of cycles. For the range of 200 to 20,000 cycles, the relationship of stress to crack initiation cycles and to test termination cycles was found to be semi-logarithmic (linear trend of stress versus log (cycles)) (see figure 5 and 6). The relationship of stress to crack propagation cycles (defined as the difference of crack initiation cycles and test termination cycles) was found to be linear (see figure7). For the range of loads investigated, the crack propagation phase is dependent on the level of load applied, and can be a relatively small part of the total test time (order of 10~20 percent) for the lower load level used in this study. The crack initiation data could be used to validate methodology for fatigue life evaluations. The crack propagation data could be used to validate methodology for damage-tolerance evaluations [2].

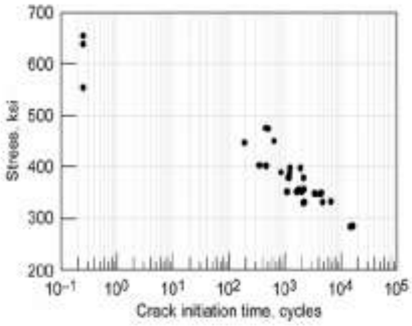

Figure-5- Variation of Crack Initiation Time with Stress

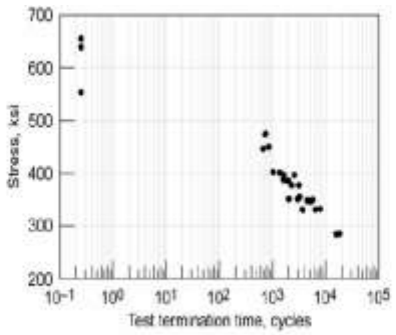

Figure-6- Variation of Crack Termination Time with Stress

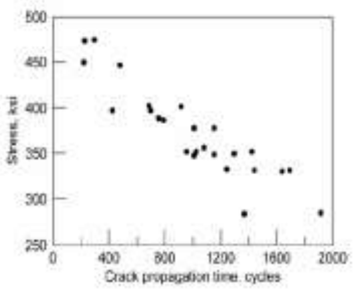

Figure-7- Variation of Crack Propagation Time with Stress

9. Factors affecting Fatigue Strength

Various factors affecting the fatigue strength are described below.

9.1 Material Composition

The materials are divided into two groups namely ferrous and non-ferrous. For ferrous metals, fatigue limit is well defined and has a fixed value after 10^6 or 10^7 stress cycles. In non-ferrous metals or alloys, fatigue limit is established at a life of 10^8 or 10^9 or even larger number of cycles except Titanium. Titanium shows same behavior as that of ferrous metals.

9.2. Grain Size and Grain Direction

Fine grained metals have superior fatigue properties than coarse grained material of same composition. In Austenite steel and many non-ferrous alloys, as grain size increases, there is degradation of fatigue properties. Superiority of grained metals becomes less significant at elevated temperature. For cyclic loading, across (transverse) grain direction gives inferior fatigue properties than along (longitudinal) grain direction.

9.3. Welding

Both welded and bolted/riveted have less fatigue strength than monolithic part of same material. The possibility of crack in weld is due to-

-Post cooling shrinkage stress
-Incomplete penetration
-Lack of fusion between weld metal and parent metal on prior weld run
-Overlap of weld metal due to overflow beyond fusion zone
-Porosity due to faulty welding techniques
-Geometric stress concentration due to welds with surface defects

9.4. Geometric Discontinuity

Even part is made of ductile material, which is affected less than brittle, the component may strongly get affected by geometric discontinuity. The seriousness of notches, holes, fillets, joints and other stress raisers depends upon relative dimension, type of loading, notch sensitivity, surface roughness .The geometric discontinuity tends to concentrate the stress and propagate the region of probable fatigue failure.

9.5. Surface Condition

It is extremely important ant factor influencing on fatigue strength. Rough surface generally shows inferior properties compared to smooth surface. Cladding, Plating and coating decrease the fatigue strength. Zn, Cd has less effect on fatigue strength, whereas Ni, Cr-plating has substantial adverse effect, Thicker the layer of plating or coating, more adverse will be the effect.

9.6. Size Factor

Smaller specimens are observed to have greater fatigue strength than larger specimen and machined parts subjected to cyclic bending stresses. This is because larger surface has greater surface area and greater volume to nucleate the crack.

9.7. Residual Stresses

It plays important role in overall fatigue properties. If the induced stress is tensile, fatigue life diminishes, whereas if it is compressive, fatigue life is improved. A common method to induce Residual stresses and to improve fatigue life includes shot penning, cold rolling and pre-stressing. Reason for the beneficial effect of residual compressive stress is, fatigue crack find more difficult to propagate through compressive stress field. Nit riding or carburizing produces compressive residual stresses whereas chromium plating produces tensile residual stresses.

9.8. Operating Temperature

Fatigue strength increases below room temperature and diminishes above room temperature.

9.9. Corrosion

Corrosive environment tends to lower fatigue strength of engineering material by large amount. Tap water or salt spray environment may reduce fatigues strength even more drastically for some material. Certain solvents and cleaning agents used to clean the surface may have adverse effect on fatigue strength. For Example, CCl_4 used on titanium, especially at high temperature.

9.10. Fretting

It leads to drastic reduction in fatigue strength of machined parts. Under certain conditions; the strength may be reduced to 1/3rd of strength without fretting. It reduces the basic strength of aluminum alloy by factor 3 and Titanium by factor 8.

9.11. Operating Speed

If operating speed is 200-700 cycles/min, it has little effect on fatigue strength at low temperature. If operating speed is less than 200cycles/min, there is small decrease in fatigue strength. Fatigue strength is improved for operating speed700-60000 to 90000cycles/min and it will sharp decreases, if operating speed is greater than 60000-90000cycles/min.

10. Methods to improve Fatigue Life

There are two practical lessons to be considered in order to improve fatigue strength. They are-

a) Metallurgical lessons to choose the best metals & alloys and most favourable mechanical or thermal treatments.

b) Lessons in design are to consider the influence of various details of shape, such as holes, notches, change of section and surface finish and to avoid accidental fatigue failure by rational design of components.

In majority of cases as high as 90%fatigue failures are due to design or machine defects while 10% due to internal faults in materials. Some other factors are discussed below.

10.1. Tempering

Fatigue limit is maximum after tempering at 350-4500c, when the impact strength is minimum. But it is desired to combine the high fatigue limit with good impact strength. So it is required to increase tempering temperature to about 6000C.Rapid cooling after tempering is recommended.

10.2. Surface Treatment

Introducing compressive stress into surface specially those which are parallel to bending. The mechanical methods also introduce surface hardening, with increase in strength of surface layers and remove surface defects due to machining or to presence of non-metallic inclusions,

Knowledge of protective coating in presence of corrosive agents,

Cold Working,

Using ductile materials than hard materials as they have less notch sensitivity,

Nit riding

Using polished surface

10.3. Residual Surface Stresses

Residual stresses are included by sharpening, cold rolling, pre-stressing. The compressive residual stresses are more beneficial as fatigue crack finds difficult to propagate through compressive stress field.

10.4. Stress Concentration

By reducing stress concentration we can improve fatigue life .Methods to minimize material so as to reduce stress concentration are,

Use of multiple notches

Removal of undesirable material,

Drilling additional holes

To avoid stress concentration at key way, two holes are drilled on each side of key slot

10.5. Operating Speed

For most of materials as operational speed increase, endurance limit increase in range of 7000-90,000 cycles/min. At high speed the time of application of maximum stress in each cycle is very short and insufficient for applied stress to exert its full effect in deforming and damaging the material.

10.6. Rest Period

It is found that there is an improvement in soft iron and carbon steel when test piece were subjected to alternating stages, superior to fatigues limit and left at rest. Rest period is generally 12 to 72 hours at temperature 500^0 C. During rest period internal stress are relieved and in such way, it increases fatigue strength.

10.7. Corrosion

If we are able to minimize corrosion in presence of fatigue stress, then fatigue strength is improved. Pitting corrosion in gear can be avoided by rational tooth form of adequate tooth form dimensions, careful machining and use of proper lubricants. Cavitations -Corrosion can be avoided by decreasing pressure difference using proper material etc. Fretting corrosion can be avoided by using lubricants, graphite oils, and grease. However good results can be obtained using oils with additions of aluminum caps

11. Conclusion

The crack is initiated at the point of the maximum principal stress in a gear tooth root. The fatigue process leading to tooth breakage in a tooth root is divided into crack initiation (Ni) and crack propagation (Np) period, which enables the determination of total service life as N = Ni+Np. At low stress levels, almost all service life is spent in crack initiation and crack propagation consumes very less part of service life (approximately only 10-20 percent). Various factors influence the fatigue strength of components .Fatigue life can be improved by adopting various methods as per application requirement. Stresses will be considered as (i) independent of the load cycle and (ii) equi-biaxial, with equal normal components in the axial (parallel to the gear axes) and tangential (tangent to the involutes profile) directions, This may not be always true in practical cases, so there is further scope for evaluating the fatigue life by considering these parameters

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