Mode and cause of failure of a Bevel gear-A review

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Abstract: gears are machine elements which used to transmit motion and power by the successful engagement of teeth. Two gears engaged with each other, the “gear” is having the larger number of teeth and the "pinion" is having the smaller number of teeth. It is said to be failed when any component is unable to perform one or more of its functions well before its expected service life. Bevel gears are widely used to transmit motion and power at shaft angle of 90° or else and it is widely used in gearbox. If it fails it is a major problem considering criticalness as it will fail to transmit motion and power and the whole assembly will fail to work.

Keywords: *Bevel gear, failure analysis, mode of failure, cause of failure.*

I. INTRODUCTION

A necessary part of an industry is always been a gear drives. This leads to the fact that industrial personnel require a good working knowledge of gearing. Basically there are four basic types of gears mostly used in industrial gearing. [1]

A gearbox includes gears, shafts and bearings assembled in a closed lubricated housing and it is widely used in the transmission system. They are available in a broad range in terms of sizes, capacities and speed ratios. A prime mover provides input and it is used to convert the input into an output with lower speed and higher torque. [2] A noiseless operation is the most important thing in any machinery so well defined characteristics of the gear system has become necessary. In the automobile industry more number of gears is used as compared to other industries so higher reliability and lighter weight gears are necessary considering the demand of lighter automobiles. If it is possible to reduce engine noise then it promotes the production of quieter gear pairs so further noise reduction is done. [2]

A straight bevel gear is shown in Figure-1.1. It is used when power is to be transmitted between two intersecting shaft and teeth are formed on conical surfaces.

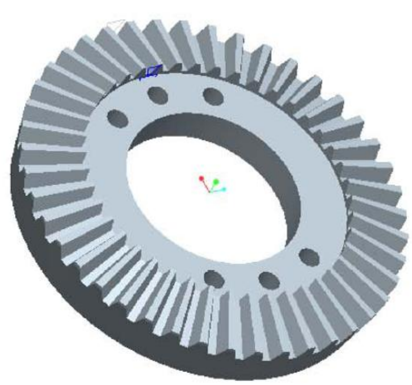

Fig.1.1 Bevel gear

If teeth are cut in the form of circular arc so the tooth is no longer straight, then it is known as spiral bevel gear. And when shafts are offset and nonintersecting hypoid gears are used. It is quite similar to spiral bevel gears.
For motor transmission differential drives, valve control and in many mechanical instruments bevel gears are used. There are many types of tooth [3] forms are possible as following,

• Straight bevel gears
• Spiral bevel gears
• Zerol bevel gears

As name suggests, in straight bevel gear a straight tooth form cut parallel to the cone axis. If it is extended, it would pass through a point of intersection on the shaft axis. Normally shafts which need to transmit power at 90° to each other bevel gears are used. They are also designed for other angles. Straight bevel gears when they mesh with each other, they are having the abrupt line or flank contact between teeth. This leads to a very noisy operation. This abrupt meshing invites high impact stresses. So if it is under heavy loads or at high speeds, there is a possibility of tooth breakages and gear failure. Due to all these reasons, straight bevel gears are only used for low speed power transmission. [3]
As name suggests, a spiral bevel gears have curved teeth. The teeth are formed along a spiral angle to the cone axis. The most commonly used spiral angle is 35° with the inclusion of pressure angle 20°. In spiral bevel gear the gears engage more gradually. The contact commences at one end of the tooth that increases until there is contact across the whole length of the tooth. This reduces the risk of tooth breakage and a smoother transmission of power is also enabled. As a result of this, spiral bevel gears are quieter and it requires smaller diameter for the transmission of same load than straight bevel gears. These are main advantages why spiral bevel gears are preferred over straight bevel gears. Spiral bevel gears are recommended for medium speed power transmission. Zerol bevel gears are recommended at higher speed power transmission. It requires high precision finished gears. Zerol bevel gears have a zero spiral angle with tooth form in curved shape. They fall in the category between straight and spiral bevel gears. Generally they produce smoother and quieter operation as compared to straight bevel gears. But main disadvantage is that they do produce side loads. [3]

1.1 FORCE ANALYSIS OF BEVEL GEAR

There are three forces which act on a particular tooth of the bevel gear. The resultant of these three forces is indicated by W which will act as shown in Figure-1.2.

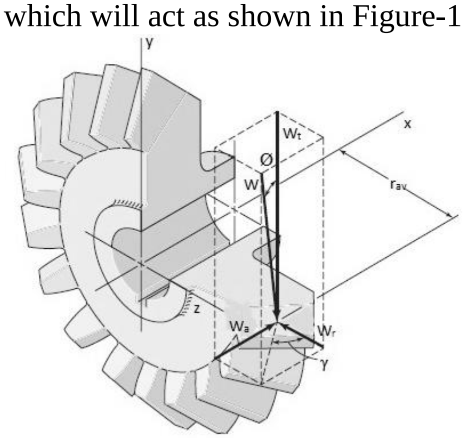

Fig.1.2 Bevel gear [3]

Due to W_t force the gear will have the rotation motion and it represents tangential force. W_r and W_a forces represent the radial force and axial force respectively. These three forces are acting perpendicular to each other and resultant of these three forces will represent W. [3]

1.2 VARIOUS MODES OF GEAR FAILURES

The mode of failure and cause of failure are two different things so it is extremely important to distinguish between them [4]. Sometimes it is confusing when two terms are intermixed. So it is necessary find out cause of failure to prevent future failures.

1.2.1 Wear: It is a surface occurrence in which upper layers of metal are eliminated mostly from the contacting surfaces of the mating gear teeth.

a) Polishing**:** It is a very slow wearing-in process in which the asperities of the contacting surfaces are gradually worn off until a very fine, smooth surface develops.

b) Moderate Wear**:** The type of wear classified as moderate takes place over a relatively long period of time. The contact pattern indicates that metal has been removed in the addendum area; also, the pitch line begins to show as an unbroken line.

c) Excessive Wear**:** This is simply normal wear which has progressed to the point where a considerable amount of material has been removed from the surfaces. The pitch line is very prominent and may show signs of pitting.

d) Abrasive Wear: When abrasive wear has taken place, contacting surfaces show signs of a lapped finish, radial scratch marks or grooves, or some other unmistakable indication that contact has taken place.

e) Corrosive Wear: This is a deterioration of the surface due to chemical action. It is often caused by active ingredients in the lubricating oil, such as acid, moisture and extreme-pressure additives.

1.2.2 Pitting: A surface fatigue failure which occurs when the endurance limit of the material is exceeded, a failure of this nature depends on surface contact stress and number of stress cycles.

a) Initial Pitting: Initial pitting occurs in localized, over-stressed areas; it tends to redistribute the load by progressively removing high contact spots. Generally, when the load has been redistributed, the pitting stops and the contact surfaces smooth over.

b) Destructive pitting: In this type of pitting the surface pits are considerably larger in diameter than those associated with initial pitting.
The dedendum section of the drive gear is often the first to experience serious pitting damage.

c) Spalling: Spalling is similar to destructive pitting except that the pits are usually larger in diameter and quite shallow. Often the spalled area does not have a uniform diameter. Spalling often occurs in medium-hard material, as well as in highly loaded fully hardened material.

d) Case Crushing: Although not considered a pitting failure, case crushing may appear similar in that damage has occurred on the contacting surface. It occurs in heavily loaded case-hardened gears, such as those which are case- carburized or nitride.
Failure often occurs only on one or two teeth of a pinion or gear; the other teeth appear to be undamaged.

1.2.3 Scoring: Rapid wear resulting from a failure of the oil film due to overheating of the mesh, permitting metal to metal contact; this contact produces alternate welding and tearing which removes metal rapidly from the tooth surfaces.

a) Frosting: As the name implies, the wear pattern appears frosted. Frosting occurs in the early stage of scoring. Usually the dedendum section of the driving gar is the first to show signs of surface distress, although frosting can first show up on the addendum section.

b) Moderate Scoring: In this type of failure, a characteristic wear pattern shows up on the addendum or dedendum of the gear teeth, often in patches. Generally, hard gears appear more frosted. Softer gears show some frosted appearance along with fine radial tear marks.

c) Destructive Scoring: This type of failure shows definite indications of radial scratch and tear marks in the direction of sliding. Often material has been displaces radially over the tips of the gear. Also, there are indications that considerable material has been removed from above and below the pitch line, and the pitch line itself stands out prominently.

d) Localized Scoring: This scoring similar to moderate scoring, takes place in localized areas along the contacting pattern of the gear teeth. Scoring is usually concentrated in these areas and does not spread across the full face width of the contacting gears.

1.2.4 Fracture: Whenever a gear tooth bears overload and if it goes beyond its endurance limit then it may cause breakage of whole tooth or a portion of a tooth.

a) Fatigue Breakage: Gear-tooth failure form bending fatigue generally results from a crack originating in the root section of the gear tooth. The whole tooth, or a part of the tooth, breaks away. Most often there is evidence of a fatigue “eye” or focal point of the break. The break shows signs of fretting and conventional smooth beach marks in the break area. Generally there is a small area that shows a rough, jagged appearance, indicating this was the last portion of the tooth to break away.

b) Overload Breakage: An overload fracture results in a stringy, fibrous break showing evidence of having been pulled or torn apart. In harder materials the break has a finer stringy appearance but still shows evidence of being pulled apart abruptly.

c) Random Fracture: Gear-tooth breakage is usually associated with the root-fillet section of the gear tooth; however, breakage failure can occur in other portions of the gear tooth. Sometimes, the top of a gear tooth will break away or large chips will fatigue away from the end of a tooth.

d) Rim and Web Failure: The rim of a gear usually fails between two adjacent teeth. Cracks propagate through the rim and into the web. Sometimes, cracks appear in the web near the rim and web junction without disturbing the rim itself.

1.2.5 Plastic Flow: Cold working if the tooth surfaces, caused by high contact stresses and the rolling and sliding action of the mesh; it is a surface deformation resulting from the yielding of the surface and subsurface material, and is usually associated with the softer gear materials-although it often occurs in heavily loaded case-hardened and through-hardened gears.

a) Cold Flow: In this type of failure, the surface and subsurface material shows evidence of metal flow. Often surface material has been worked over the tips of the gear teeth, giving a finned appearance. Sometimes the tooth tips are heavily rounded-over and a depression appears on the contacting tooth surface.

b) Rippling: This is a periodic wave-like formation at right angles to the direction of sliding or motion. It has a fish-scale appearance and is usually observed on softer tooth surfaces under certain conditions. Rippling is not always considered a surface failure, unless it has progressed to an advanced stage.

c) Ridging: This is the formation of deep ridges by plastic flow of surface and subsurface material. It shows definite peaks and valleys or ridges across the tooth surface in the direction of sliding.

1.3 FAILURE ANALYSIS PROCEDURE

If it is able to get the answers of the following three questions then it is said that the failure analysis investigation [4] is complete and successful.

1) What is the mode of failure?

2) What is the most probable cause of failure?

3) How can failure be prevented in the future?

It is a fact that failure of any machine component results from some sort of a mistake or error like design error, manufacturing error etc. causing a dump in the path of the continuous process of engineering design manufacturing-performance. Therefore, to perform any complete and perfect failure analysis investigation one has to consider service conditions, manufacturing, and design.

By considering various stress and loading conditions, the most probable cause of failure is been scored out and that indicates the weakest section of the gear tooth. Subsequently, it becomes possible to determine possible means by which future failures is prevented.

II. LITERATURE REVIEWED

M. Fonte et al [5], a failure analysis investigation of two helical gear wheels of a ducted azimuth thruster is performed in this paper. The determination of the damage root causes of material including fracture examination is performed during this research work. At the start of failure analysis two broken teeth of two helical gear wheels were kept under observation. For micro level analysis, scanning electron microscope (SEM) was used. It is concluded that failure was caused by localized overstress on the teeth surface. By observation it is concluded that the fatigue crack initiation started at the root of coast side flank of the gear teeth, followed by the crack growth, and final fracture. Mode of failure for both gear wheels is clearly the same. In assistance with a poor lubricating oil performance in a gearbox, a continuous overloading of the thrusters is also the main root cause for this failure. An inappropriate lubrication caused the severe contact stress on gear teeth were clearly analysed in SEM. The premature failure also gives the evidence of a possibility of misalignment between the pinions and the gear wheels.

Myounggu Park [6], in this paper an accessory gear box of a turbojet engine was investigated. The material used for the manufacturing of drive bevel gear is AISI: 8617. The fracture is the probable mode of failure. With the visual inspection of the fractured surface it is clear that the cracking mode was fatigue. In this paper also SEM is used for the micro level study. From that it is clear that there is no surface defect. The fatigue crack initiation took place at the upper root area of the gear teeth and propagated intergranularly. The cracking route indicates the way of typical tooth bending fatigue. This is due to the improper surface heat treatment. Analysis at micro level indicated that the failed gear was not properly case hardened and because of that the surface hardness decreased drastically. All these evidence indicates that it was a typical tooth bending failure.

S.K. Bhaumik et al [7], the investigation of failure analysis took place over a helicopter which caught with an accident. The reason found was the failure of an intermediate gear box. Examination showed that the driving gear was fractured due to fatigue cracking with ultimately leads to gearbox failure. The teeth of the gear were severely damaged. This type of damage only occurs in hardened material under severe load. Its evidence proves that it is due to spalling. Micro level observation reveals that there was more than one fatigue crack initiation at the tooth root regions. Improper assembly and misalignment of two mating gears shaft may also lead to teeth failure and ultimately gear failure.

Nauman A. Siddiqui et al [8], the failure of any component in an aircraft structure or in engine leads to the failure of whole assembly and it may cause accident and as a result of this there will be loss of human lives. Most of the accident cases which take place in aircrafts are due to the failure of power transmission unit or any component in power transmission assembly. Most of the gear failures occur due to design errors, manufacturing error, assembly error, maintenance error, etc. The investigation of the cause of failure of bevel gears in an engine train of an aircraft has performed to avoid this sort of loop holes in future. The microstructural investigation indicates the transformation of retained austenite into untempered martensite under higher internal shear stress. Using DEA in the case the availability of internal stresses was validated. Subsurface cracks were developed within the altered orientation of DEA under the effect of this stresses. The variation in loading induces concentrated higher shear stress at the crack front and non-uniform fatigue distributions were produced in the crack propagation region combined with overloading. In this study mode of failure founded was contact fatigue. The continuous rolling action of gears resulted in tooth bending which produced crack at the fillet root. The drastically change in hardness at die etching area between case and core which resulted in the complete detachment of case after sever deformation of core. The case of the driven gear teeth was removed and excessive wear also took place. This happened only because of simultaneous rolling and sliding of meshing gear teeth in the existence of dust and rust particles. Higher internal stresses cause the formation of un-tempered martensite from retained austenite and micro-cracks. These all can be eliminated with the use of proper surface hardening between core and case of the gear and post heating processes. So now the condition is that there is gradual change in hardness from case to core at die etching area.

Tezcan Sekercioglu et al [9], in differential gear box spiral bevel gear play an important role in transmitting motion and power. Investigation of spiral bevel gear fracture used in truck differential gear box manufactured from case hardened steel is included. Visual inspection, case and core hardness, chemical analysis and different metallurgical tests were performed on the specimen made from the spiral bevel gear to identify the cause of failure. It was observed that there were pitting on gear surfaces. The fracture was considered under the effect of micro structure. Hardness values at core and case were found lower than what required. The obtained contact stresses were higher as compared to the permissible stresses. From this study it is said that to get same hardness and microstructure, similar chemical composition is necessary for the two mating gear materials. Case hardness is quite low as compared to the requirement so it should be increased. The case should also be properly carburizing heat threatened to get the required and proper depth of the case. As there were quite higher contact stresses and the gear was against overloading the gear geometry should be optimized to reduce the contact pressure. As the contact pressure was higher so proper lubrication should be provided to eliminate the pitting occurrence at the surface of the gear.

R.C. Yin et al [10], in this paper, investigation was made with the use of SEM, metallographic and micro hardness testing. It was examined that the gear was subjected to serious pitting and associated tooth breakage. Because of that a spiral bevel pinion inside a gear reducer was failing. A spiral bevel pinion suffered under repeated contact stress and repeated bending stress. Due to all these stresses the pinion surface was under severe stress resulted in surface pitting. In gear or pinion failures there is not a case that always gear fails due to material deficiency or poor mechanical properties of the material. It may also fail due to misalignment between to two mating gears or due to a design error or manufacturing error. All these things also lead to the premature failure of the gears so alignment of the gear should also be checked at the time of assembly.

N.Mohan Raj et al [11], this paper show the three dimensional fillet stress analysis of bevel gear tooth using FEM and APDL. Uniformly varying load and a concentrated load are applied at pitch point to evaluate the stress distribution at the root of the tooth. Load distribution on pitch the line and the stress distribution at the root of fillet is also included in this study. 3D model and analysis of the bevel gear is done with the use of ANSYS. Two different conditions are used to evaluate the influence load on the root stress in straight bevel gear. From that it is found that the stresses are higher at toe side and comparatively lower at heel side in a gear tooth.

Vilmos Simon et al [12], in this paper, to minimize tooth contact pressure and transmission error, the modifications are to be made by changing head-cutter geometry and machine tool settings to get optimum tooth geometry. So misalignment will be produced between driver and driven gear and point contact is replaced with line contact. The correlation between pinion tooth modification and contact pressure is also studied.

Faydor L. Litvin et al [13], this study mainly focuses on the improvement of the bearing contact, transmission error, reduction of noise, vibration, to avoid severe contact stresses and results of experimental tests of bevel gears. It also includes the design, manufacturing, stress analysis and reduction in value of transmission error. FEM is used to get the tooth contact analysis and stress analysis. From the all above study, it is concluded that proper approach to design, simulation and stress analysis leads to the optimal solution of contact, reduced transmission errors, reduce in severe contact stress, noise, vibration, to obtain an oriented path of contact, to avoid or reduce area of severe contact stresses. With the use of Top-Rem blades, the endurance of spiral bevel gear drives can be increased.

III. CONCLUSION

The work presented here represents the overview of an important role of the mode and cause of failure in bevel gear failure analysis.

(1) Bevel gears are mostly used in the transmission gearbox to transmit motion and power.
(2) So if bevel gear fails, the whole assembly will fail to work.
(3) Mostly the mode of failure for bevel gear is tooth breakage or fatigue.
(4) And mostly the cause of the failure is overloading, misalignment of the shaft axis, material deficiency, and mechanical property of the material.
(5) A transmission error, a design error, a manufacturing error and an assembly error also leads to the gear failure.
(6) Higher contact stresses including lower lubrication film between two mating gears and debris present in the lubricant also lead to severe gear surface worn out.
(7) Die etching area (DEA) also plays an important role in gear design as if contact stress increases up to certain limit, case of the gear tooth will be sheared out. This happens mainly because of the drastically change in the hardness between case and core of the gear tooth.

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