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Fatigue failure of a helical gear in a gearbox

Osman Asi *

Department of Mechanical Engineering, Usak Engineering Faculty, Afyon Kocatepe University, 64300 Usak, Turkey

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Abstract

This paper presents a failure analysis of a helical gear used in gearbox of a bus, which is made from AISI 8620 steel. The helical gear had been in service about three years when several teeth failed. The failed helical gear had a number of adjacent teeth and random teeth breakage at one end of teeth. 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. The failure zones were examined with the help of a scanning electron microscope equipped with EDX facility. Results indicate 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.

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Keywords: Helical gear; Fatigue; Misalignment; Pitting; Spalling

1. Introduction

Helical gears are widely used as power transmitting gears between parallel or crossed shafts, since not only can they carry larger loads but also the dynamic load and the noise level experienced during the operation are minimum.

Gears can fail in many different ways, and except for an increase in noise level and vibration, there is often no indication of difficulty until total failure occurs. In general, each type of failure leaves characteristic clues on gear teeth, and detailed examination often yields enough information to establish the cause of failure. The general types of failure modes (in decreasing order of frequency) include fatigue, impact fracture, wear and stress rupture [1]. Fatigue is the most common failure in gearing. Tooth bending fatigue and

* Tel.: +90 276 2634195; fax: +90 276 2634196.

E-mail address: osmanasi@aku.edu.tr.

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 [1,2].

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 [1,3,4].

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 [1,3].

A bus repair shop of a worldwide-accredited bus brand received a passenger bus with a problem with its helical gear of transmission gearbox. The bus repairing shop requested a failure analysis investigation. Chief technician of the bus repair shop reported that helical gears were often failed with similar damage in operation. The gearbox in this case was reported to be running hot and with excessive vibration. The



Fig. 1. General appearance of the failed helical gear.

Table 1
Basic data of the failed helical gear

Parameters	
Number of teeth helical gear	36
Helix angle (°)	15
Module, normal (mm)	4
Pitch circle diameter (mm)	150
Outer diameter (mm)	158
Face width (mm)	42

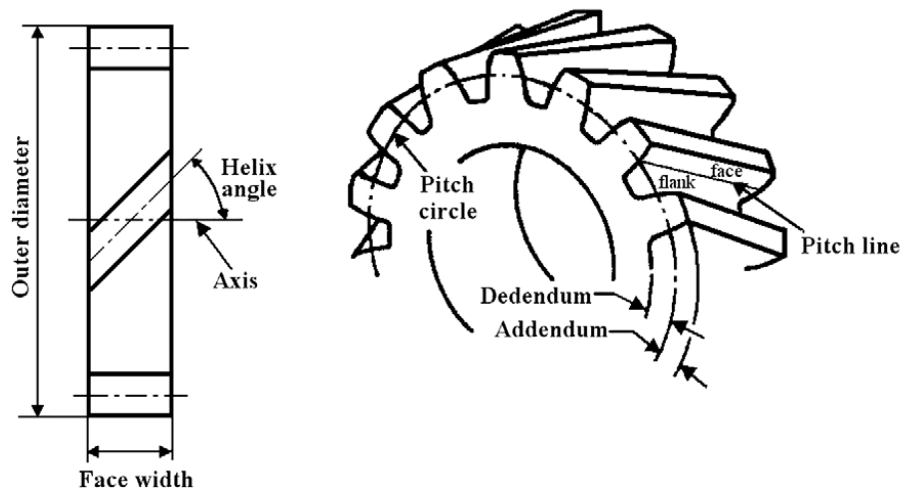


Fig. 2. Nomenclature of the helical gear teeth.

general appearance of the failed helical gear is shown in Fig. 1. The helical gear, fourth speed drive gear, had been in service about 3 years when several teeth failed. The bus has six-speed gearbox and 275 kW at 2200 rpm engine power. The basic data of the failed helical gear is given in Table 1. For convenience, relevant nomenclature of a helical gear is shown in Fig. 2.

In the present study, a failed helical gear used in gearbox of a bus has been examined for the cause of failure.

2. Experimental procedure

The failed helical gear was inspected visually and macroscopically; care was taken to avoid damage of fractured surfaces. The failed helical gear was subjected to optical microscopy, photo documentation, chemical analysis and micro-hardness measurement both at the failure zone and away from the failure zone. The fractured surfaces were ultrasonically cleaned and examined with the help of a scanning electron microscope (SEM) equipped with EDX facility.

3. Results and discussion

Chemical analysis using atomic absorption spectrophotometry was carried out at several locations of the failed helical gear hub and the average values of the test results are given in Table 2 along with the specified

Table 2
Chemical composition of the failed helical gear and AISI 8620 steel

Element	Failed helical gear	AISI 8620 steel (individual values are maximums)
% C	0.192	0.18–0.23
% Si	0.219	0.20–0.35
% Mn	0.756	0.70–0.90
% Ni	0.494	0.40–0.70
% Cr	0.473	0.40–0.60
% MO	0.157	0.15–0.25
% S	0.0091	0.040
% P	0.016	0.040

chemical composition. Spectrum analysis and micro-hardness measurement revealed that the failed helical gear material was AISI 8620 steel as carburised, which is usually used for gears in the surface-hardened conditions. The micro-hardness distribution across the helical gear tooth thickness at the pitch line was measured using a Vickers hardness tester with 1 kg load, and the results are given in Fig. 3. Also, the core and surface hardness were measured to be 439 and 686 HV, respectively. The carburized case depth was found to be about 0.63 mm. Carburized case depth is defined as the depth from surface where hardness reaches a value of 550 HV.

A specimen from the pitted area of one gear tooth was metallographically prepared and observed in an optical microscope in both unetched and etched condition. In the unetched condition, significant fatigue cracks were observed at the pitch line region due to destructive pitting or spalling, as shown in Fig. 4. This crack orientation was typical of all the significant cracks observed. Optical microscopy view of case microstructure of the failed helical gear tooth after etching with Nital solution is shown in Fig. 5. As shown, the case microstructures consist of martensite (which appears dark) and retained austenite (which appears white). This is typical of case hardened steel. No abnormality was observed in the microstructure.

Visual examination of the failed helical gear showed that a number of adjacent teeth and random teeth failed by fatigue, as shown in Fig. 1. Typical macro-fracture appearance of the failed helical gear tooth is shown in Fig. 6. The fracture surface presents typical features of fatigue failure. Similar fracture appearance was also observed on the other fracture surface of the gear teeth. A triangular piece of the gear teeth had broken off like large chips at one end of teeth. These pieces are as wide as one-third of the face width. The fracture surface of the tooth exhibits a distinct crack initiation site (indicated white arrow) and progressive

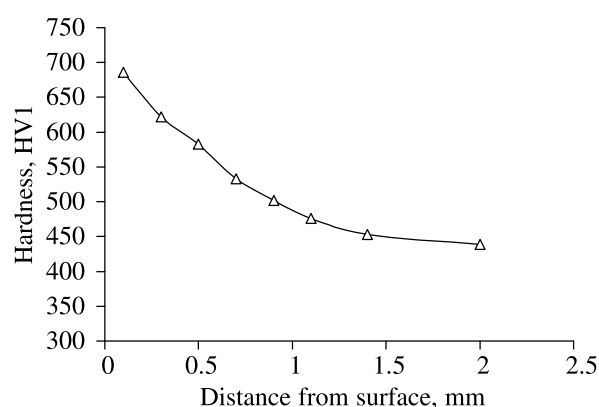


Fig. 3. Hardness distribution across the helical gear tooth thickness at the pitch line.

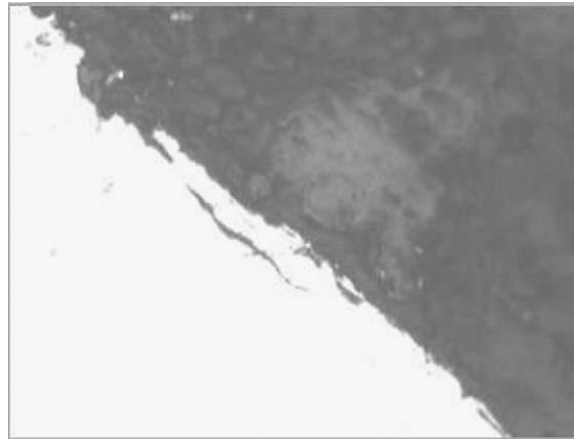


Fig. 4. Unetched metallographic cross section through gear tooth showing typical fatigue crack formed by pitting at the pitch line.

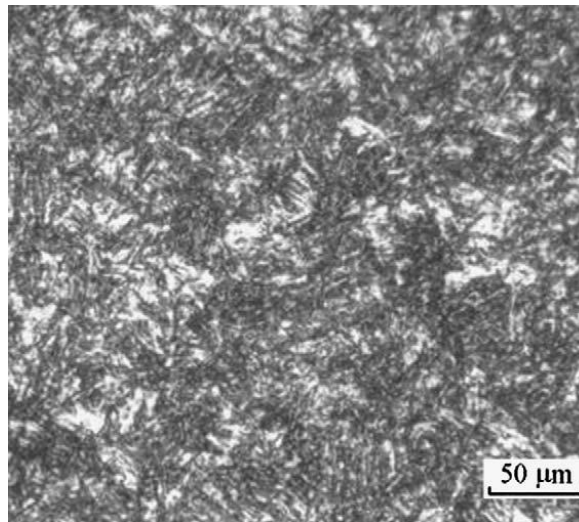


Fig. 5. Microstructure of the tooth showing a mixture of martensite and retained austenite.

flat fatigue fracture region, and the final fracture region. The crack initiation region and beach marks could be seen clearly with naked eye. The origin of the crack was at the pitch line region close to one end of the teeth. In all cases, the crack initiation sites were close to one end of the gear teeth, suggesting that the loads were highest in this region. This implies that there was incorrect contact between the gear teeth, possibly resulting from misalignment. The origin of the crack was surrounded by curved beach marks. Also, the fracture surface at the fatigue region had a smooth appearance with a rippled beach mark pattern. Visual inspection indicated that fatigue had initiated at the pitch line region and had grown out towards the roots of the teeth. A small area has a rough, jagged look where the last portion of the tooth broke away. No corrosion media were found on fracture surfaces.

Destructive pitting and spalling were also noted on the active (i.e. loaded) side of each tooth at one end of tooth at the pitch line, as shown in Fig. 7. Destructive pitting appears as much larger pits than initial pitting. These larger craters usually are caused by more severe overload conditions. Spalling is similar to destructive pitting except that the pits are usually larger in diameter and quite shallow. Often the spalled

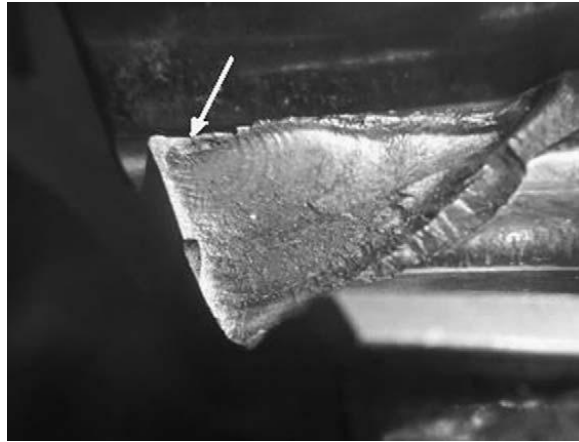


Fig. 6. Higher magnification photograph of the fracture surface of the failed helical gear tooth.

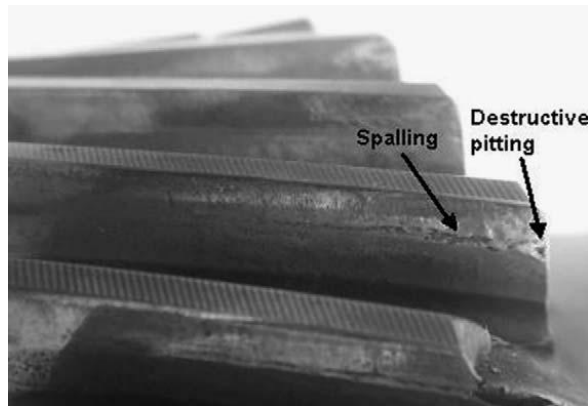


Fig. 7. Photograph of the pitted gear teeth. Note, spalling and destructive pitting at one end of tooth at the pitch line.

area does not have a uniform diameter. A spalling cavity consists of a shallow wall and a steep wall. Both the shallow and steep walls have jagged surfaces. It originates below the surface, usually at or near the case/core transition zone. Spalling is usually caused by excessively high contact stresses. Usually, large pits are formed; because stress levels are high, the edges of the initial pits break away rapidly and large irregular voids are formed. Often these voids join together [3,4].

The fractured surfaces and tooth surface of the failed helical gear were examined with the help of a scanning electron microscope (SEM) in order to identify the cause of fatigue crack initiation and propagation. Fig. 8 shows crack initiation and propagation region. Beach marks can be observed clearly on the fracture surface, which is a typical feature of fatigue failure [3]. Beach marks indicate that the fatigue crack penetrated a large portion of the tooth before a piece broke off. The fracture surface is characteristic of a high cycle fatigue failure. River-like pattern could be seen in the propagation zone, which is a typical feature of fatigue failure, as shown in Fig. 9.

Semiquantitative chemical analysis was carried out by EDX attached to SEM on the fracture surface to qualitatively determine the helical gear chemistry and to verify the presence of any other associated components. All the elements in the steel were found to conform to specification of AISI 8620 steel. The EDX examination of damaged regions did not reveal any detrimental elements.

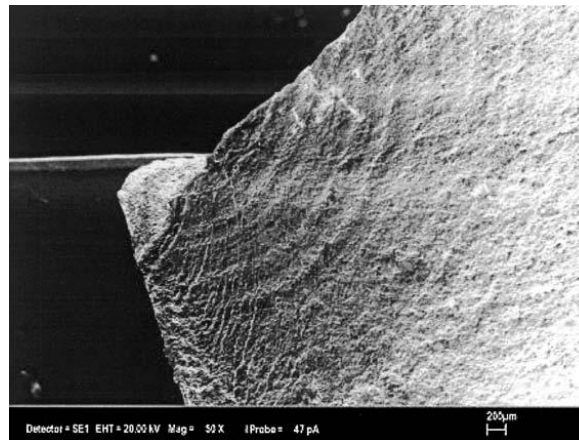


Fig. 8. SEM micrograph showing the crack initiation and propagation region.

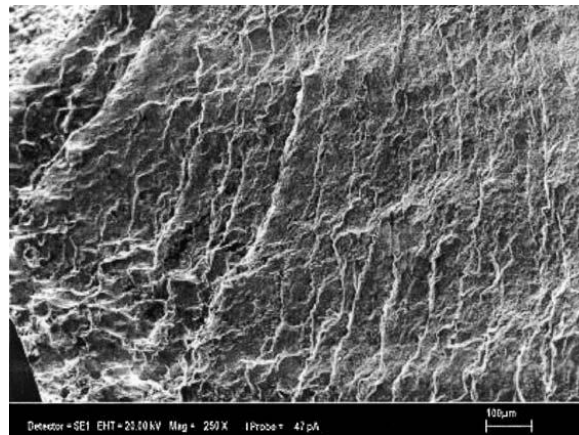


Fig. 9. SEM micrograph showing typical brittle fracture observed in the crack propagation region.

SEM examination indicated that although there were destructive pitting and spalling area on the active side of the gear tooth in the area of the pitch line (Fig. 10), there was micropitting in some areas in the dedendum section of the gear tooth (Fig. 11). The area immediately above or below the pitch line is very susceptible to pitting. Not only is the rolling pressure great at this point but sliding is now a real factor [1]. Spalling regions and fatigue cracks initiation sites from spalling region at the pitch line of the failed helical gear tooth can be seen clearly, as shown in Fig. 10. In addition, Fig. 10(a) shows top view of developing spalls in the vicinity of the pitch line.

From the above observations, it is clear that teeth breaks are not typical tooth bending fatigue failures. Tooth bending fatigue is one of the most common modes of fatigue failure in gears. Since the maximum tensile stresses occur at the root radius on the active flank of the gear tooth, gear-tooth failure from bending fatigue generally results from a crack originating in the root section of the gear tooth [1,2]. The whole tooth, or a part of the tooth, breaks away. 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. These failures are typically caused by high stress concentrations at a particular area from such things as minute grinding cracks, foreign materials in the gear mesh, improper heat treating, pitting, or misalignment. Gears that are case hardened by carburizing are the most susceptible to gear tooth failure by

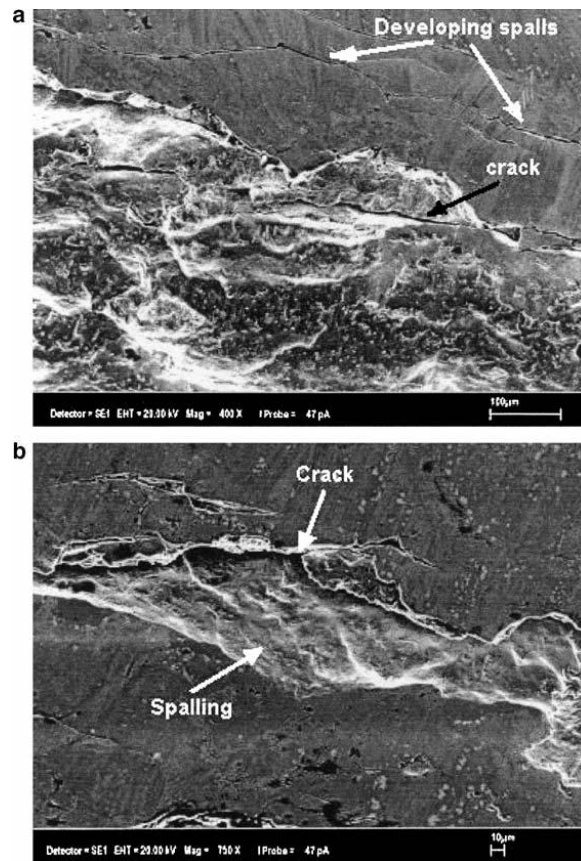


Fig. 10. SEM micrograph showing two damaged area at the pitch line at the different magnification. Note, spalling areas containing cracks and developing spalls in the vicinity of pitch line.



Fig. 11. SEM micrograph showing a typical pit caused by pitting on dedendum surfaces of the tooth.

breakage after pitting [3]. When a gear is damaged by pitting, a crack can start at a pit, spread lengthwise, and go all the way through the tooth. On wider-face-width gears, a triangular piece of tooth often breaks out. This piece may be as wide as one third or one-half of the face width [3]. Also, due to misalignment, the

pinion does not mesh properly with the gear during operation and this lead to a high stress concentration at the particular area. If a pinion or gear continues in service after an appreciable part of the tooth is gone, the now-overloaded remainder of the tooth is likely to break off. Sometimes, even though several teeth have portions broken off, the gears continue in service because the increased noise and vibration are not enough to attract attention [1].

SEM analysis showed that the destructive pitting and spalling area are located in the vicinity of the pitch line. Fatigue cracks originated from these damaged areas and propagated subsurface. In other words, it was proved that the tooth fracture is caused by destructive pitting and spalling and does not involve other damage processes. Why, in this situation, did destructive pitting and spalling occur along pitch line? Once the contact point moves into the vicinity of the pitch line, the number of gear pairs in contact becomes minimal, so that the normal Hertzian contact stresses is maximum on this region. Surface contact fatigue can occur when two surfaces slide against each other under high contact pressure and cyclic loading. This mode of failure leads to crack initiation at or near the contact surface, and may subsequently lead to damage varying in extent from microscopic pitting to severe spalling. Pitting is usually caused by gear tooth surfaces not properly conforming to each other or not fitting together properly. This can be a result of minor involute errors or local surface irregularities, but most often it occurs because there is not proper alignment across the full face width of the gear mesh [1,3].

In the case of helical gears, the contact line is a diagonal one emerging as a point at the beginning of contact from a point low on the flank near the tooth root and gradually grows to lines of varying length up to the contact line passing through the tip of the first face of the gear tooth. On further rotation, the length remains constant for some time and then diminishes gradually to a point at the tip of the last face where the contact ends. Thus, the contact line moves gradually along the whole range of the face width, covering the tooth flank and face. However, because of the occurrence of elastic deformation (deflection) on the surface of loaded teeth and misalignment in service, contact occurs along narrow bands or in small areas instead of along the expected line contact [1,5].

From the above analysis, due to misalignment that was present, the pinion did not mesh properly with the helical gear during operation and this led to a high stress concentration at one end of tooth at the pitch line. Under the cyclic loading, destructive pitting and spalling occurred at one end of tooth at the pitch line, and then fatigue cracks have initiated at these stress concentration points leading to fracturing of the part of helical gear tooth. It is well known that if there are pitting, not only can this lead to a high stress concentration, but can also cause fatigue crack initiation during operation [1,3]. When the local stress exceeds the material yield strength, it is possible to form a fatigue crack.

4. Conclusion

This study was conducted on a failed helical gear used in gearbox of a bus. Spectrum analysis and micro-hardness measurement revealed that the failed helical gear material was AISI 8620 steel as carburised. The composition, microstructure, hardness and the case depth were found to be satisfactory and within the specification. Fractographic features indicated that fatigue was the main cause of failure of the helical gear. On the fracture surface of the teeth, the crack initiation region and beach marks could be seen clearly with naked eye. It was observed that the fatigue crack originated from destructive pitting and spalling areas in the vicinity of tooth pitch line and propagated toward tooth region of tooth. Failure analysis results indicate that a part of tooth fatigue failure in this case was, therefore, as a result of an incorrect load distribution on the gear teeth. It was concluded that the primary cause of failure of the helical gear was likely a misalignment of the helical gear. Formation of the destructive pitting and spalling at one end of tooth in the vicinity of the pitch line, and all the fatigue crack initiation sites that were close to one end of the gear teeth supported this hypothesis.

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