Failure Analysis on Rear Gearbox Output Gear of Helicopter

LIU Changkui，ZHANG Bing，CHEN Xing，TAO Chunhu，LIU Delin

AVIC Failure Analysis Center, Beijing Institute of Aeronautical Materials, Beijing 100095, China

Abstract: A tooth of a rear gearbox output gear in a helicopter fractured after service for a period. The failure mode and causes of the gear were analyzed by macro and micro observation, hardness and carburized depth testing, microstructure examination, roughness and round angle measurement. The results show that the fracture surface exhibited fatigue fracture characteristics. It is concluded that the gear failed by fatigue fracture. The crack initiated from the working face of the dedendum round angle. The working face round angle of the gear is smaller than required, resulting in stress raisers, which is the main cause for the fatigue fracture of the gear. It is recommended that the manufacturing processes of the dedendum round angle should be concisely controlled.

Keywords: Gear; Fatigue; Helicopter

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 include fatigue, impact fracture, wear and stress rupture[1]. Fatigue is the most common failure mode for gears. Tooth bending fatigue and surface contact fatigue are two of the most common modes of fatigue failure for 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 [1-3].

Rear gearbox output gears are important dynamic transfer parts for helicopters. After service for a period, a tooth of a rear gearbox output gear in a helicopter fractured. The output gear was made of 16Ni3CrMoE steel. In the present work, a comprehensive investigation was carried out in order to identify the failure mode and cause of the gear and suggest corrective measures.

2. Experimental

2.1 Macroscopic observation

The appearance of the failed gear is shown in Fig.1. A tooth fractured at the dedendum round angle. According to the propagation steps, it can be assumed that the crack initiated from the working face at the dedendum round angle. The source is a linear source. Obvious beach marks can be seen. The fatigue region almost accounts for 80% of the whole fracture surface, shown in Fig.2. At the working face of other teeth, black regions can be seen can be seen, as shown in Fig.3. After acid erosion, these regions still present black. These regions have coarse wear trace and the machining trace of these regions is not more serious than that of other regions, so it can be assumed that the damage of these regions is burning damage during service. At the addendum top of the teeth, wear and collision traces can be seen, shown in Fig.5.

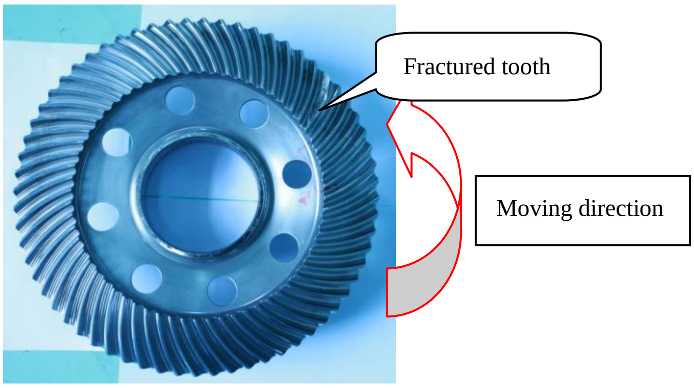


Fig.1 Macro appearance of the failed gear

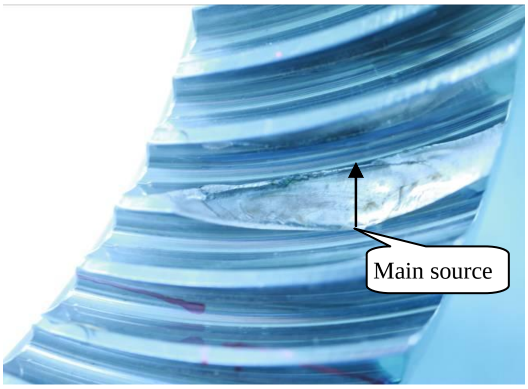


Fig.2 Macro appearance of the fractured tooth

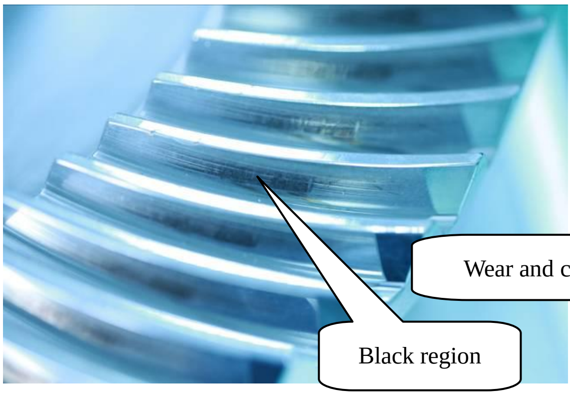


Fig.3 Wear trace at working face of other teeth

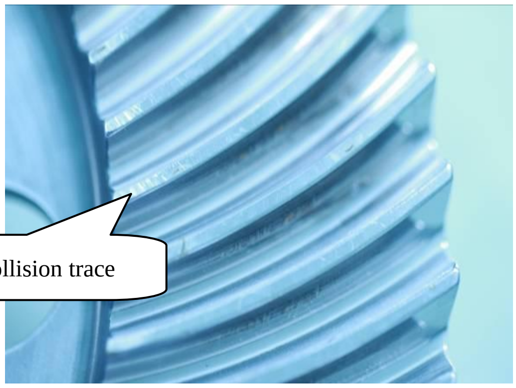


Fig.4 Wear and collision trace at addendum top

2.2 Microscopic observation

Micro observation shows that there exists obvious wear at the source region. No other damage is found at the source region, shown in Fig.3. Machining trace can be found at the lateral face near the source, shown in Fig.4. Because of serious wear of the fracture surface, the depth of the machining trace at the source region cannot be accurately measured. Fatigue striations can be seen at the propagation region, shown in Fig.5. The fast fracture region is covered with dimples, shown in Fig.6.

The black regions at the working face of other teeth present shelling-off feature due to serious wear, shown in Fig.7. EDS analysis results show that the oxygen content of these regions is about 4.7%. At the working face near the top and at the top of some teeth, parallel wear trace can be seen, shown in Fig.7. During normal service, the top of the teeth of the output gear wouldn't be in contact with the bottom of the teeth of input gear. According to the parallel wear trace at the top of teeth, it can be assumed that axial float had happened to the gear. The parallel wear trace is shallow, short, and parallel, so it can be assumed that they formed a short time ago. Namely, they occurred after the tooth fractured. The direction of the working face wear trace of the teeth is the same as that of the top wear of the teeth, so it can also be assumed that they are also related to the axial float.

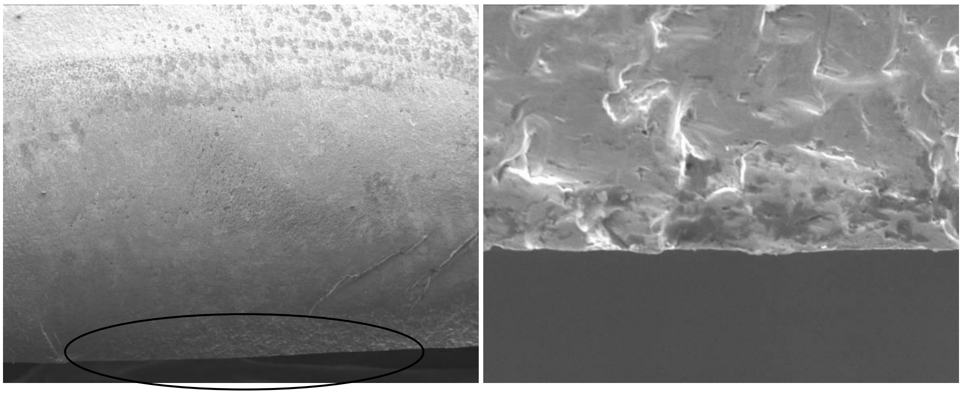


Fig.5 Low-magnification appearance of the main source region

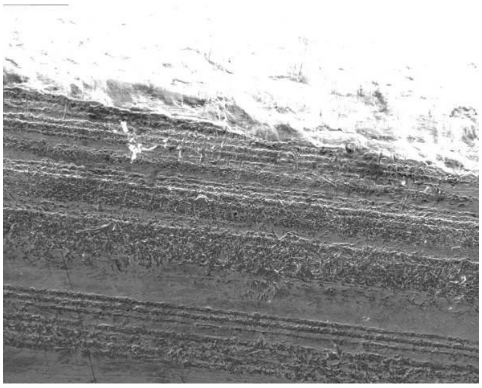


Fig.6 Machining trace near the main source

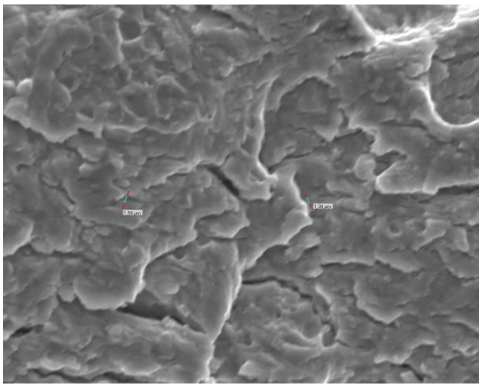


Fig.7 Fatigue striations at the early propagation region

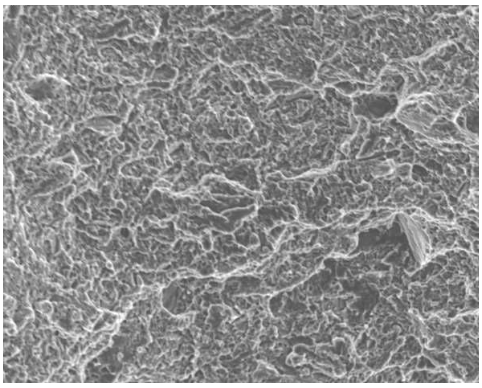


Fig.8 Dimples at the last fracture region

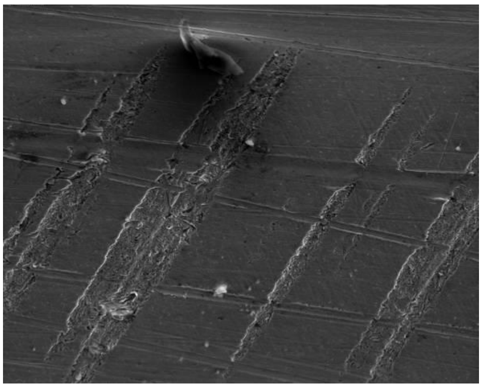
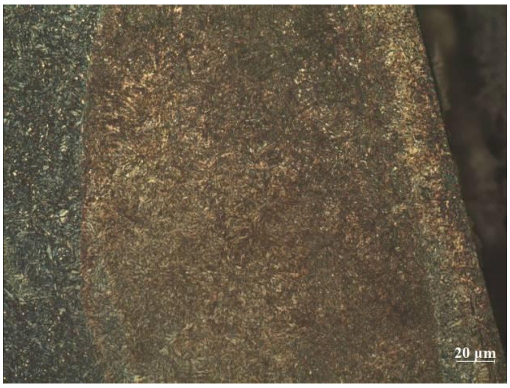


Fig.9 Appearance of black region of working face   Fig.10 Parallel wear trace at the working face near the tooth top

2.3 Microstructure examination

Metallographic specimens perpendicular to the burn tooth face were cut down from the teeth near the fractured tooth. A burn surface layer can be seen, composed of needle-shaped martensite and residual austenite(Fig.7). The core region is composed of lath-shaped martensite and residual austenite, shown in Fig.9. The number of the inclusions in the gear tooth is relatively small.



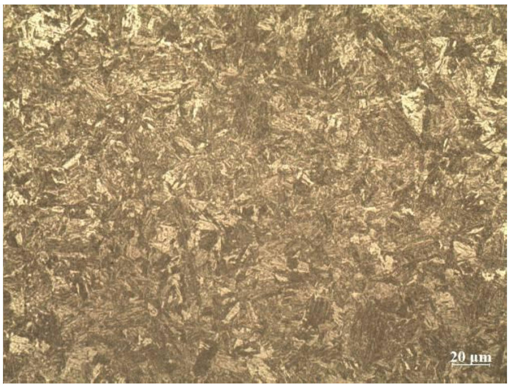


Fig.11 High-magnification burn structure near the surface   Fig.12 Microstructure of core region of gear tooth

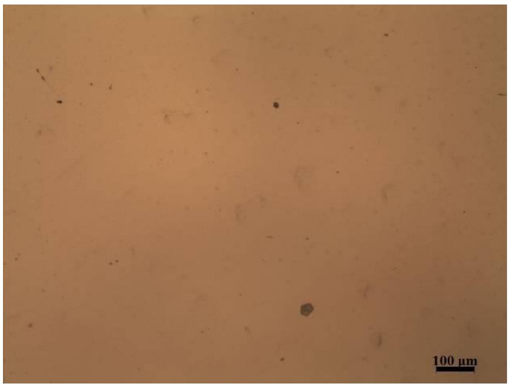


Fig.13 Inclusions in gear tooth

2.4 Hardness and carburized depth testing

Samples perpendicular to the working face were cut down from the teeth near the fractured tooth to test hardness and carburized depth. The hardness about 0.15mm away from the surface is HV669~HV679, meeting the requirement(⩾HV660). The core hardness of the gear is HRC44.76, within the required range of HRC33~45. The carburized depth of the working face is 1.40mm, and that of the dedendum round angle is 1.21mm. The carburized depth of the non-working face is 1.30mm, and that of the dedendum round angle is 1.04mm. They all meet the requirement of 0.8~1.6mm.

2.5 Round angle measurement

The dedendum round angle of three successive teeth near the fractured tooth were measured. The results are shown in Table 1. It is found that the round angle at the working face side is R0.525~0.769, far lower than the required R1.6±0.1. The round angle at the non-working face side is R0.690~0.862, also far lower than the required range.

Table 1 Measurement results of dedendum round angle

Testing position		Round angle value R / mm
Working face	1# round angle	0.525
	2# round angle	0.727
	3# round angle	0.769
Non-working face	1# round angle	0.826
	2# round angle	0.690
	3# round angle	0.862

2.6 Roughness measurement

The roughness of working face, non-working face and dedendum round angle was measured. According to the measurement results, the roughness of working and non-working face, R_a, is 0.1~0.2μm; that of dedendum round angle is 0.5~0.6μm. All meet the requirement(⩽1.6μm).

2.7 Quantitative analysis on fracture surface

In order to work out the crack propagation life, quantitative analysis on the fracture surface was carried out by using the width of fatigue striations as a key parameter. Fatigue striations can be seen at the area 1.084mm to 12.64mm away from the source. The space between the striations in the extension region was measured as fatigue propagation rate. By curve fitting, the relationship between crack propagation rate and crack length was obtained, shown in Fig.10. The results show crack propagation rate increased with the rise of crack length. Then fatigue propagation life was obtained by listing trapezoidal method. The results show the fatigue propagation life is 33432 cycles.

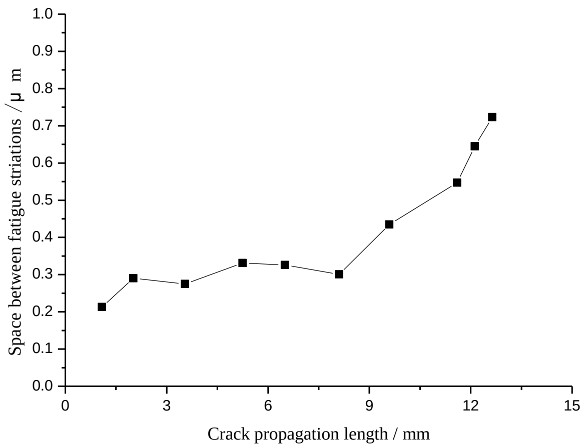


Fig.10 Relationship between crack propagation rate and crack length

3. Discussion

According to the beach marks and fatigue striations at the fracture surface, it can be assumed that the gear failed by fatigue fracture. The fatigue region almost accounts for 80% of the whole fracture surface, so it can be further assumed that the failure mode of the gear is high-cycle fatigue. The fatigue crack initiated from the working face at the dedendum round angle, and propagated in the depth direction. Based on quantitative analysis on fracture surface, the propagation life between the point 1.084mm away from the surface source and the last point where fatigue feature can be seen is 33432 cycle.

Surveying gear failure cases in the literature reveals that there are many causes for gear failure, including faulty design, poor manufacturing and heat treatment practices, improper installation and operation, and poor maintenance. One or more of these causes may lead to surface and or subsurface deteriorations, stress concentration, impact or continuous overloading which, in turn, lead to eventual failure of gears. Fatigue fracture is found to be the most common fracture mode, and most fatigue cracks originated at the surface or subsurface of gears, because the possibility for creating stress raisers, the key ingredient for fatigue crack initiation, is the greatest at the surface or subsurface. Pitting, sharp notches, surface deteriorations, poor machining and grinding marks are examples of stress raisers at the surface. Internally initiated fatigue cracks due to faulty materials and poor heat treatment practice, such as inclusions and other inhomogeneities, are rare[4-6].

From the observations, it is clear that the tooth fracture is typical bending fatigue failure. Tooth bending fatigue is one of the most common modes of fatigue failure for gears. Since the maximum tensile stresses occur at the root round angle at the working face side of the gear teeth, 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. The microstructure, hardness, carburized depth and roughness are satisfactory and within the specification. According to round angle testing results, the working face round angle of the gear teeth is far smaller than required, which would result in stress raisers and promote the initiation of fatigue cracks. In order to improve the fatigue life, the manufacture processes of the gear should be concisely controlled.

4. Conclusion and recommendations

The gear failed by fatigue fracture. The crack initiated from the working face of the dedendum round angle. The working face round angle of the gear teeth is smaller than required, resulting in stress raisers, which is the main cause for the fatigue fracture of the gear. It is recommended that the manufacturing processes of the dedendum round angle should be concisely controlled.

References:

[1] Failure analysis and prevention. ASM handbook, vol. 11. Metals Park (OH): American Society for Metals; 1986.

[2] Fernandes PJL．Tooth bending fatigue failures in gears．Engineering Failure Analysis，1996，3：219–225．

[3] Asi Osman．Fatigue failure of a helical gear in a gearbox．Engineering Failure Analysis，2006，13(7)：1116–1125．

[4] Samroeng Netpu, Panya Srichandr. Failure of a helical gear in a power plant．Engineering Failure Analysis，2013，32：81–90．

[5] Martin R, Karen S. Fatigue failure of carburized steel gear from a helicopter transmission. In: Handbook of case histories in failure analysis. OH: ASM International; 1992. 228–230.

[6] Becker WT, Shipley JR, editors. Failure analysis and prevention, ASM handbook, vol. 11. OH: ASM International; 2007. 718–720.