Fracture Failure Analysis of Gear Teeth

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Abstract: Gears are important transmission components in the field of aviation industry. Failure cases such as fatigue fracture and fatigue spalling often occur due to poor conditions, and the status of teeth surface is usually one of the important elements for the failure cause analysis, but few have analyzed how the machining status of gear end surface affects the fracture failure. In this paper, one engagement failure of two gears was studied, and the failure phenomenon is as follows: all teeth of the driving gear fractured, two adjacent teeth of the driven gear fractured and several locations of teeth bottom cracked. According to the fracture morphology of the gear, it is judged that the driven gear fatigue-cracked firstly, and the fatigue zone is located at the lower end surface rather than the tooth bottom. Material structure, machining status of gear end surface, and the thickness of nitriding layer were inspected. In addition, the difference of the machining status between the lower and the upper end surface was analyzed. The results show that compared to the upper end surface, the lower end surface is smoother and the grinding amount is relatively larger. The residual stress tested by XRD shows that there is a residual compressive stress of about 84 MPa on the upper end surface and a residual tensile stress of about 238 MPa on the lower end surface. The tensile stress and the working stress cause the local stress level of the lower end surface of the gear to be higher than the fatigue strength, causing fatigue cracking from the lower end surface.

1. Introduction

In the aviation industry, gears are an important part of transmitting power and motion. The reducer, speed governor and tail reducer of engines all have gears for power input or output transmission [1]. In the harsh environment of high speed and heavy load, failure often occurs to gears. The failure of gears will cause the accuracy retention, running stability and service reliability of the entire transmission system to decline, and ultimately may cause serious accidents [2]. There are many reasons for gear failure, including improper design, improper machining and heat treatment methods, improper installation and operation, and improper maintenance. The common failure modes of gears include tooth surface wear, gluing, contact fatigue, plastic deformation, and tooth fracture[3]. The machining factors
that cause the failure of gears are generally rough surface machining marks on the tooth surface, causing surface stress concentration, and promoting fatigue cracking or fatigue spalling [4]. There are few reports on the influence of gear end face machining on gear failure.

This article starts with a gear failure analysis, introduces the analysis and judgment of the causes of gear failure, and deeply discusses the influence of gear end machining on gear failure. As the analysis object of this article, the gear has seriously damaged. The teeth of the driving gear have all broken and several teeth of the driven gear have also broken. The material of the driving and driven gears is 30Cr3WA, the tooth surface is nitrided, the depth of nitride layer is 0.15–0.38mm, the hardness of the nitrided layer ≥700HV, and the matrix hardness is 28–37HRC. This article aims to improve the analysis technology of the broken gear teeth, deepen the understanding of the effect of gear end machining state on gear failure, and improve the safety and reliability of gear service.

2. Experimental and results

2.1 Macro morphology of broken gears
The driving and driven gears failed after working for less than 50 hours. The driving gear has a serious “tooth gnawing” phenomenon, and the damages of all the teeth are similar. There is material accumulation at the root of the tooth, and the part of teeth unmeshed with the driven gear is relatively in good condition. Two adjacent teeth of the driven gear have broken, and tooth crest of other teeth is deformed and worn, as shown in Figure 1. There is a high temperature color on the lower end surface of the driven gear, where there are cracks on both sides of multiple tooth bottoms, as shown in Figure 2. There is no crack on the upper end surface.

![Figure 1. Gear failure morphology](image1)

(a) the driving and driven gears  (b) the driving gear damage  (c) the driven gear injury

2.2 Microscopic observation of fracture
The driving gear fracture characteristics are dimples and wear marks, which illustrate the failure mode is overload, as shown in Figure 3. The micro morphologies of the two fractures of the driven gear are similar: the source area is located at the lower end surface of the tooth root edge, fatigue striations can be observed at the fracture expansion area, and the fatigue expansion of the fracture is relatively
sufficient, as shown in Figure 4. The small cracks is artificially opened, and the same phenomenon can be observed, such as source area located at the lower end surface of the tooth root edge, and fatigue striations at the expansion area, as shown in Figure 5.

![Figure 3. Microscopic morphology of broken teeth of driving gear](image)

![Figure 4. Fracture of driven gear](image)

![Figure 5. Microscopic morphology of the fracture after opening crack on the lower end of the driven gear](image)
2.3 Material organization and hardness test
The cross-sectional structure of the driving and driven gears is the same, and the surface is nitrided, where the veined nitrides distributed along the grain boundary are not obvious, and the core is sorbite, where no abnormal microstructure is found.

The depth of the nitriding layer of the driving and driven gears is 0.217mm (tooth bottom) and 0.163mm (middle teeth), both of which meet the technical requirements.

The hardness of the nitriding layer of the driving and driven gears are 662.3HV and 691.0HV, respectively, slightly lower than the technical requirements.

The matrix hardness of the driving and driven gears is 33.6HRC and 40.5HRC, respectively, and the hardness of the driven gear is slightly higher than the technical requirements.

3. Analysis and discussion

3.1 Analysis of the first broken gear
According to the fracture characteristics of dimples, it can be assumed that the failure mode of the driving gear is overload fracture. And based on the residual tooth phenomenon at the unmatched part, it can be assumed that the driving gear fractured under the action of rapid impact.

According to the fatigue striations on two similar teeth fracture surface, it can be assumed that the failure mode of the driven gear is fatigue fracture. Based on the sufficient fatigue expansion of the fracture surface, it can be assumed that the working stress is at relatively low level, which could not cause the impact overload of the driving gear.

Thus, the driven gear fatigue-cracked firstly, and two adjacent teeth fractured, leading to the driving gear and the driven gear failing to match with each other, which causes the driving gear fractured by impact load.

3.2 Analysis of failure causes
In the process of the transmission of force and changing speed, there is both rolling and sliding between the meshing tooth surfaces, and the tooth surface is also subject to pulsation or alternating bending stress, which may cause the force of the gear in three types, such as the friction between the meshing tooth surfaces, the contact stress of the meshing tooth surfaces, and the bending stress of the gear, and the corresponding types of gear damage are tooth surface wear, contact fatigue, and bending fatigue[5]. Combined with the fracture characteristics of the driven gear in this article, it can be known that it belongs to bending fatigue failure. Under bending stress, the root of the tooth is prone to damage, as a result of the highest level of stress[6]. The source area on the fracture surface of the broken tooth and the source area of the small crack are located on the lower end surface of the gear, not at the tooth root. It shows that there is an abnormality in the lower end surface of the gear, which causes the maximum stress point to be transferred to the lower end surface from the tooth root. Therefore, it is necessary to analyze the abnormality of the lower end surface.

First, the machining morphology of the upper and lower end surfaces of the driven gear was observed and compared. The upper surface is rougher, with coarser machining traces, while the lower end surface is smoother, with shallower and thinner machining traces, as shown in Figure 6, which indicate that the upper and lower end surface experienced different machining state. Further observation shows that the cracks on the lower end face are basically perpendicular to the machining direction, which share certain similarities with grinding cracks[7].
Secondly, the residual stress of the upper and lower end surfaces was tested, which is shown in table 1. The results show that the upper end surface is in a state of compressive stress, with an average value of 84MPa, and the lower end surface is in a state of tensile stress, with an average value of 238MPa. The residual stress of lower end surface is about 320 MPa higher than the upper end face. The original situation will be larger than this value, due to the cracks on the lower end face.

| Location      | Test Results | Average value |
|---------------|--------------|---------------|
| Lower end face| 248 121      | 364 316 326   | 238           |
| Upper face    | -142 -90     | -135 -6 -112  | -84           |

Finally, the thickness of the nitriding layer of the upper and lower end surface was observed, as shown in Figure 7. The results show that the thickness of the nitriding layer of the upper end surface is about 0.112mm, significantly higher than the lower end surface with a thickness of 0.068mm, and the machining volume of the lower end surface is significantly higher than that of the upper end surface.

The upper and lower end surfaces of the gear are different in machining traces and machining volume, resulting in different state of residual stress on the upper and lower end faces. In addition, it can be seen that there is high temperature color which has the same direction with the machining direction on the lower end surface, which also indicates that the machining state of the lower end face is abnormal. The
machining mode of the lower end surface is grinding machining, leading to large residual tensile stress on the lower end surface, which, combined with working stress[8], caused cracks to initiate on the lower end surface near the tooth bottom, and fatigue growth occurred.

The foregoing introduced the difference between the upper and lower end surfaces in three aspects such as machining volume, machining roughness, and high temperature color. The following analysis was conducted through these three aspects. The higher machining volume needed longer grinding time and accumulated grinding heat was enough to cause surface thermal stress, structural stress and grinding tensile stress, increasing grinding residuals stress. The shallow grinding marks and the smooth surface indicate that the abrasive grains of the grinding wheel are too small and easy to be blocked, which generated the heat not easy to cool, or the grinding wheel is long-time-used and the abrasive grains were blunt, leading to more grinding heat and increasing the tendency to produce grinding residual stress[11]. There is a high-temperature color on the lower end surface, also indicating that the cooling effect during the grinding process is not obvious, which increased the tendency to produce grinding residual stress.

4. Conclusion
(1) The driven gear damaged first, and its damage mode is fatigue fracture. The fatigue fracture of the driven gear is mainly related to the abnormal grinding of the lower end face of the gear.

(2) Abnormal grinding of the lower end face of the driven gear is manifested as a large machining volume on the lower end surface, a small machining roughness, and residual high temperature color. These abnormal machining phenomena caused a large tensile residual grinding stress on the lower end surface: the residual stress reaches 238MPa;

(3) According to the abnormal grinding characteristics, the failure of the driven gear can be avoided by adjusting the machining volume, selecting the appropriate grinding wheel, and improving the cooling capacity.

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