Fault Analysis on Bevel Gear Teeth Surface Damage of Aero-engine

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Abstract. Aiming at the trouble phenomenon for bevel gear teeth surface damage of Aero-engine, Fault Tree of bevel gear teeth surface damage was drawing by logical relations, the possible cause of trouble was analyzed, scanning electron-microscope, energy spectrum analysis, Metallographic examination, hardness measurement and other analysis means were adopted to investigate the spall gear tooth. The results showed that Material composition, Metallographic structure, Micro-hardness, Carburization depth of the fault bevel gear accord with technical requirements. Contact fatigue spall defect caused bevel gear teeth surface damage. The small magnitude of Interference of accessory gearbox install hole and driving bevel gear bearing seat was mainly caused. Improved measures were proposed, after proof, Thermoelement measures are effective.

1. Introduction
Aero-engine transmission system is mainly composed of accessory gearbox, gears, transmis Smith (fts, bearings and other parts, these parts are interrelated in the structure and interacted in the force each other which constitutes the complex power transmission components [1]. The bevel gear is an important component to change the direction of transmission, which plays an important role in the stability and reliability of the transmission system.

In the working state, the engine rotor transmits the power to the attachment by the bevel gear which installed on the accessory case; In the starting state, the starter transmits the power to the engine rotor by the bevel gear on the opposite path. In the process of bevel gear transmission power, due to the manufacturing and installation errors, motion impact, sliding friction, circulation of alternating bending stress and other factors , The bevel gears could produce metal material fatigue on the teeth surface and cause teeth surface wear, pitting, gluing, peeling and other teeth surface damage, affect the bevel gear movement accuracy and work stability, result in vibration and noise, reduce the life of the bevel gear, the bevel gear tooth broken, transmits failure, engine stop work [2, 3]. Therefore, study and analyze the failure mechanism of bevel gear teeth surface damage, develop the process improvement measures, prevent the gear transmission fault are very important.

2. The phenomenon of trouble
The driving and driven bevel gear were inspected after a certain type of aero engine test, all driving bevel gear tooth convex have been serious wear and spall, all driven bevel gear tooth concave pitch
circle has been serious wear and spall, as shown in figure 1. Further inspection found that the four nuts and lock plates of the driving bevel gear bearing seat have been loosened. The surface of bearing seat has serious wear marks, the local wear depth has 0.14mm. The outer diameter of the bearing seat has abrasion marks, the bearing roller of driving bevel gear has abrasion marks, the rack is badly worn, and the driving and driven bevel gear are scrapped.

![Fig. 1 Bevel Gear Teeth Surface Damage](image)

3. Fault location
This paper lists all the possible causes of the fault from the working environment, design, processing, assembly, lubrication and so on. Taking the damage of bevel gear teeth surface as the top event, the fault tree is drawn according to the logical relationship, as shown in figure 2. The investigation and analysis are carried out one by one.

![Fig. 2 Fault Tree of bevel gear teeth surface damage](image)

3.1. high starting speed and overload
The aero engine has two starter generators QF12-1. The power of each starter generator is 12Kw, the driving bevel gear speed is 5930 r/min, the starting speed is about 2372 r/min, the driven bevel gear speed of 5660 r/min, starting speed of about 2264 r/min, gear geometric parameters are shown in table 1.
Table 1. Geometric Parameters of Bevel Gear

| Parameter              | driving bevel gear | driven bevel gear |
|------------------------|--------------------|-------------------|
| Large end modulus m(mm)| 4                  | 4                 |
| Number of teeth z      | 21                 | 22                |
| Normal pressure angle α| 20                 | 20                |
| Sub-cone angle δ       | 43.7               | 46.3              |

The bevel gear teeth are mainly subjected to three forces: circumferential force, radial force and axial force. The circumferential force of the driving bevel gear is opposite to the steering force, and the circumferential force of the driven gear is the same as the steering force; The radial force of the driving and driven gears points respectively to the respective gear center, and the axial force is directed to the large end by the small end of each gear. The calculation formula is as follows:

circumferential force:

\[ F_c = 2000 \frac{T}{d} \]  \hspace{1cm} (1)

radial force:

\[ F_r = \frac{F_c}{\cos \beta} \left( \tan^2 \beta \cos \delta + \sin \beta \cos \delta \right) \]  \hspace{1cm} (2)

axial force:

\[ F_a = \frac{F_c}{\cos \beta} \left( \tan^2 \beta \cos \delta - \sin \delta \cos \delta \right) \]  \hspace{1cm} (3)

The relevant parameters were substituted into the formula (1), (2), and (3), the torque was calculated to be 96.6 N.m, and the circumferential force was 2300N, and the radial force and axial force were all 575N.

According to the result of the calculation, when the engine is started, the single tooth of the bevel gear is subjected to a circumferential force of 2300N (230kg), the load is large, and the driving bevel gear is 2372 r/min, the driven bevel gear is 2264 r/min, During high speed and overload, the bevel gear support system is deviation and abnormal meshing of the gears. The increase of the contact stress of the gear teeth surface which lead to teeth contact deformation, and the tooth surface of the gear is damaged [4].

3.2. The design is not reasonable

3.2.1. The small magnitude of interference of driving bevel gear bearing seat and the installation hole of the accessory case. The material of accessory case is ZM-5 magnesium alloy, the linear expansion coefficient is 23 × 10^-6 (1 / °C), the bearing seat material is 12CrNi3A, the linear expansion coefficient is 11.5 × 10^-6 (1 / °C), The working temperature is about 100 °C, bearing seat outer diameter is 82 mm, according to the calculation formula of linear expansion:

\[ \Delta d = \Delta t \times \alpha \times \phi d \]  \hspace{1cm} (4)

According to the formula (4): in the working state, the installation hole of the accessory case will increase by 0.15mm, and the outer diameter of the bearing seat will increase by 0.075mm, and the
coordination between will increase by 0.075mm. The magnitude of interference of driving bevel gear bearing seat and the installation hole of the accessory case is 0.045 mm, the hole of accessory case and the bearing seat of driving bevel gear are interference in assembly and become clearance in working condition. Under the action of alternating stress, the bearing seat in the radial direction will produce the periodic, small amplitude vibration, changing the bearing and gear working conditions, resulting in the wear of the bearing and gear; At the same time, the vibration of the bearing seat in the radial direction gradually offset and tighten the screw pile, due to the nut loose, so that the bearing seat and the driving bevel gear sink, increasing the gear meshing gap, changing the gear meshing position, the teeth contact position move to the big end, and the big end and small end of the teeth root bending stress redistribution, So that the meshing between the teeth load distribution is uneven, the teeth surface contact stress is uneven distribution, the teeth local contact stress concentration, exacerbate the gear wear [5]. Also changed the working state of the bearing, the bearing exacerbates the wear and tear after a period of time, radial clearance and axial clearance is increasing, further deterioration of the gear pair installation relationship, changing the teeth surface meshing position and installation distance of the bevel gears, increasing the gear transmission error, the teeth surface is damaged. Teeth surface damage in turn affect its support system, resulting in bearing and bearing seat wear each other, bearing seat and casing wear each other, the formation of a vicious cycle. Therefore, the smaller magnitude of interference of driving bevel gear bearing seat and the installation hole of the accessory case is the main cause of the teeth surface damage.

3.2.2. Low support stiffness of driving bevel gears. The driving bevel gear is an elongated rod-like structure, one end is supported by the spline and the other end supported by the ball bearing, support stiffness is low, and the driving bevel gears are axially displaced by the axial force, the meshing gap becomes small, the contact stress becomes larger, when the contact stress exceeds the ultimate stress of the teeth surface or sub-surface material, the teeth surface will appear small fatigue crack, with the use of time, the metal will produce wear and tear off, meshing gap becomes large, produces impact load which will make the gear wear off, serious fracture [6].

3.3. Processing error
The attachment case is easy to be processing errors in the manufacturing process. In particular, the processing error of the position of the box hole is difficult to control which results in the installation error of the bevel gear, such as the deviation of the axis intersecting angle, the angular deviation and the center distance Deviation, so that the gear produces a greater impact load and noise in the transmission process [7]. In the process, Gears are easy to produce teeth profile curvature error, pitch deviation, geometric eccentricity, imbalance in quality. Processing error affects the gear contact area length and width, which will vibrate in axial movement and radial, resulting in gear meshing Imbalance, load changes and so on; these factors will directly affect the gear meshing gap and coloring marks which can’t meet the technical requirements, assembly is difficulty, gear transmission quality isn’t high, teeth surface meshing bad, dynamic load of gear becomes big, vibration and noise of gear increase, exacerbates gear tooth surface damage.

3.4. Installation error
Installation error of the bevel gear is in a non-parallel states and changes the gear contact state, the load at the same time is asymmetrical distribution on several pairs of meshing teeth, the non-uniform distribution along the tooth meshing contact will lead to contact with one end of the contact, the local contact stress concentration, resulting in tooth profile of gear with a certain impact speed and meet the point of encounter in the process of transmission, resulting in shock, vibration and noise. Meshing gap and coloring marks of gear are one of the main indicators which check installation error of gear. The meshing gap ensures the meshing position of the bevel gear, the coloring mark ensures contact with the mark at the rated load. The smaller meshing gap will appear tooth top wear phenomenon, the larger meshing gap will appear tooth root wear phenomenon, It is serious which will lead to cut root,
the formation of pits. Coloring marks of teeth surface don’t meet the technical requirements, the gear is easy to produce partial load, teeth surface wear, strain, agglutination, peeling and other failures and occurs larger noise, vibration and impact.

3.5. Poor lubrication
In order to avoid gear wear failure, the gear must carry on the lubricating in work states, relying on the viscosity of the oil which can produce the fluid lubrication film in the working surface of teeth, It can reduce and prevent teeth surface damage, if the oil is not sufficient, viscosity is smaller or nozzle clogging. The surface of teeth isn’t easy to build bearing oil film, the gear can’t be fully lubricated to teeth surface damage.

4. Physical and chemical inspection

4.1. Energy spectrum analysis
The samples of the bever gear pair (12Cr2Ni4A) were analyzed by the spectrometer, the results are shown in table 2, which can meet the requirements.

| Element       | Ni   | Cr   | Si   | Mn   | Fe   |
|---------------|------|------|------|------|------|
| value of driving gear | 3.38 | 1.55 | 0.44 | 0.36 | surplus |
| value of driven gear  | 3.67 | 1.52 | 0.38 | 0.45 | surplus |
| 12Cr2Ni4A          | 3.25~3.75 | 1.25~1.75 | 0.17~0.37 | 0.30~0.60 | surplus |

4.2. hardness test
The test results showed that the hardness of the carbon surface of the driving bevel gear was HRC62.6, and the core hardness was HRC40.6. the hardness of the carbon surface of the driven bevel gear was HRC61.5, the core hardness was HRC41.8. hardness measurements meet the requirements of the hardness of the bevel gear.

4.3. metallographic examination
The depth of the carburizing layer was checked by the sample. Driving bevel gear carburized layer depth is 0.91 mm, the driven bevel gear carburized layer depth is 0.93 mm, the carburized layer depth accords with the requirement of bevel gear carburized layer depth.

4.4. Macro-appearance analysis of teeth surface damage
The surface wear and peeling area of the driving bevel gear is observed by Scanning electron-microscope, there are a lot of pitting and flaky peeling in the stripping zone, there are obvious signs of fatigue arc, and there are some signs of striping, and the stripping area and the striping at both ends are large number of obvious fatigue lines starting from the subsurface, as shown in figure 3.
Fig. 3 Macro-appearance of driving and driven Bevel Gear Fatigue Spall Defect

The wear and tear zone of the driven bevel gears is observed by electron microscopy, and the serious wear zone in the nodule has obvious pitting and flaky peeling. Most of the flaking pits are fan-shaped, with obvious fatigue curves starting from the subsurface, as shown in Fig. 3.

4.5. Physical and chemical inspection conclusion
(1) The material composition, metallographic structure, hardness and depth of the cementation layer of the bevel gears meet the requirements.
(2) Contact fatigue is the reason of teeth surface damage.

5. Improvement measures
(1) with reference to similar foreign models, combined with the material expansion coefficient, increase the magnitude of interference of driving bevel gear bearing seat and the installation hole of the accessory case, make sure the hole of accessory case and the bearing seat of driving bevel gear are interference in working condition, in order to enhance the fatigue strength of the bevel gears.
(2) Optimized the assembly process, carried out the study of 4 fixed nut tightening torque, and ensured that the fixed nut won't loosen in the work.
(3) Strengthen inspection after the engine test. Check the metal mark of the bevel gear, the 4 fixed nuts, locking plates and bearing seats have been moved.

6. Measures verification
After the improvement measures were implemented, the rejection rate of bevel gear was reduced from 55.23% to 18%, so the improvement measures were effective.

References
[1] GUO Mei, CHEN Cong-hui, HU Xing-hai, HOU Ming-xi. Research of the Aero Engine Accessory Gearbox Structure Design Method [J]. Journal of Mechanical Transmission, 2017.41 (3): 211-216.
[2] WANG Wen-zhong, Liu Qi-chun, Wang Wei-dong. Mechanical Damage and Preventive Measures of Fretting Wear [J]. Helongjiang Metallurgy, 2011.31 (3): 52-53.
[3] JIA Guo-hai, Gong Jin-ke, E Jia-qiang. Effect of Interference Fit on Fretting Wear of Gear Shaft Shoulder [J].Journal of Hunan university (Natural Sciences), 2013.40 (5): 31-36.
[4] CHEN S Y, TANG J Y, WANG Z W, HU Z H. Effect of Modification on Dynamic Characteristics of Gear Transmissions System [J]. Journal of Mechanical Engineering, 2014. 50 (13): 59-65.
[5] YU Han. Contact Stress and Temperature Field Analysis of Gear [J]. Mechanical Engineering & Automation, 2013.180 (5): 50-52.
[6] XU Ping. Gear Wear Failure and Repair [J]. GANSU Metallurgy, 2010.32 (1): 112-113.
[7] CAO X M., LOU J J, MA Z Y. Sensitivity Analysis of Installation Errors of the Straight Bevel Gear Modification Tooth Surface [J]. Journal of Mechanical Transmission, 2014.04: 40-43.