

Helicopter Accessory Gear Failure Analysis Involving Wear and Bending Fatigue

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TECHNICAL PAPER

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Gear tooth wear is a very difficult phenomenon to predict analytically. The failure mode of wear is closely correlated to the lambda ratio. Wear can be the limiting design parameter for long-term durability. Also, the failure mode of wear can manifest into more severe failure modes such as bending. Presented is a failure analysis in which this occurred.

A legacy aerospace gear mesh experienced nine failures within a two year time period. The failures occurred after more than eight years in service and within tight range of cycles to one another. Each failure resulted in the loss of all gear teeth with origins consistent with classic bending fatigue. None of the failures were detected prior to tooth loss.

Non-failed gears, with slightly lower time than the failed gears, were removed from service and inspected. Gear metrology measurements quantified a significant amount of wear. The flank form of these worn gears was measured and the measured data used to analytically predict the new dynamic load distribution and bending stress. To predict if the failure mode of wear was expected for this gear mesh, an empirical relationship of wear to lambda ratio was created using Rolls-Royce field data from multiple gear meshes in multiple applications.

The empirical understanding of wear coupled with the analysis was used in an analytical design of experiments (ADOE). The results of the ADOE were then used to guide design changes. Presented are the metallurgical failure analysis findings, dynamic gear mesh analysis, the empirical wear rate curve developed, results of the ADOE, and design changes.

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500 Montgomery Street, Suite 350
Alexandria, Virginia, 22314

October, 2007

ISBN: 978-1-55589-915-8

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Introduction

Gear tooth wear is a very difficult phenomenon to predict analytically. The failure mode of wear is closely correlated to the lambda ratio [1][2]. Wear can be the limiting design parameter for long-term durability. The failure mode of wear can manifest into more severe failure modes such as bending. Presented is a failure analysis in which this occurred.

Eight events occurred in a legacy aerospace gear mesh within a three-year time period. The failures occurred after more than eight years in service and within a tight range of cycles to one another. Each failure resulted in the loss of all gear teeth with origins consistent with classic bending fatigue. The failures were not detected prior to tooth loss.

Non-failed gears, with slightly lower time than the failed gears, were removed from service and inspected. Gear metrology measurements quantified a significant amount of wear. The flank form of these worn gears was measured and the measured data used to analytically predict the new dynamic load distribution and bending stress. To predict if the failure mode of wear was expected for this gear mesh, an empirical relationship of wear to lambda ratio was created using Rolls-Royce field data from multiple gear meshes in multiple applications.

The empirical understanding of wear coupled with the analysis was used in an analytical design of experiments (DOE). The results of the analytical DOE were then used to guide design changes. Presented are the metallurgical failure analysis findings, dynamic gear mesh analysis, the empirical wear rate curve developed, results of the analytical DOE, and design changes.

Nomenclature

λ	Specific film thickness, the oil film thickness divided by the composite roughness [3].
MOS	Margin of safety, the allowable value divided by the predicted value. MOS should be greater than 1.0

Chip detector	A detection device used in aerospace gearboxes to detect early failure involving metal generation
DOE	Design of experiments
R_a	Average roughness of involute profile μin
Super finishing	An isotropic chemical process performed to achieve improved surface finish
T_i	Oil inlet temperature $^{\circ}\text{F}$
W_r	Wear rate expressed in inches per cycle $\times 10^{15}$

Overview of gear system

The failed gear mesh was used to drive an electric generator installed on a Rolls-Royce gas turbine engine in a helicopter.

A schematic of the gear train is shown in Figure 1. The gear meshes are numbered one through four. Gear mesh four is the spare drive gear mesh that is the subject of this paper. The failed pinion and mating gear were carburized, ground, and shot peened AMS6265. The engine torque was input through gear mesh number one.

Background of failures

The initial indication to the pilot was generator output failure. Additionally, two aircraft had chip light indications just prior to landing. Two others had chips discovered on the magnetic plug when troubleshooting the cause of a generator problem. One aircraft had a chip light during the mission (chip detectors had large and numerous chips when examined after flight – the engine was removed and replaced). The sixth event occurred before take off with mission equipment on and blades in flat pitch position. In all cases, the aircraft generator drive shaft and spare drive gearshaft in the accessory gearbox (AGB) turned freely. Each failure resulted in all gear teeth being fatigued or milled off the spare drive gear (Figure 4).

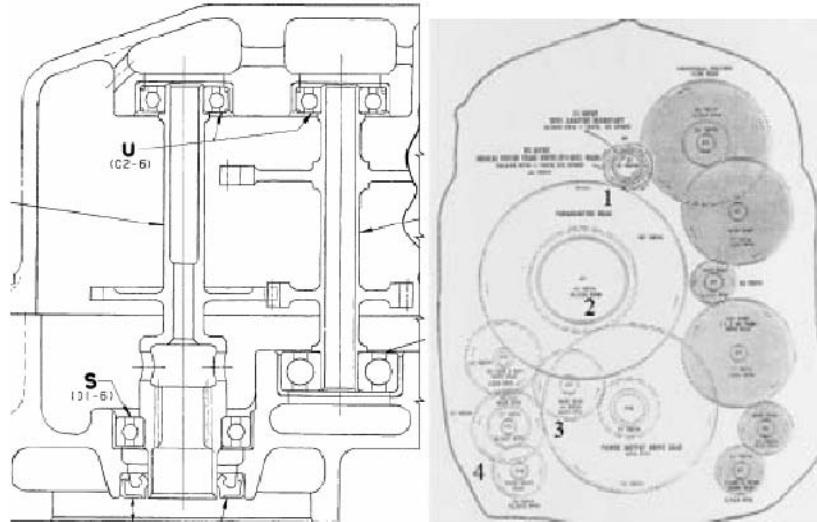


Figure 1. Schematic of gear train

Eight events occurred over a three-year period. Five of the eight were from the same fleet. The eight failures are detailed in Table 1. A lognormal probability plot was created to show the scatter in the failure data. The bending fatigue failures occurred beyond ten million cycles and within a small range of cycles as shown in Figure 2.

Failure investigation

An engineering team conducted a detailed failure investigation. Dynamics, geometry, manufacturing quality, gear design, application, lubrication quality, operation in the field, and materials were categories investigated in detail. None of these categories were identified as root cause during the investiga-

tion. The findings from each of these categories are beyond the scope of this paper and are not presented.

Table 1. Cycle and hours of failures by date

Date of failure	Time (hrs)	Cycles
Nov 2003	1297.7	9.37E+08
Feb 2004	1347.0	9.72E+08
May 2004	1577.2	1.14E+09
May 2004	1705.7	1.23E+09
Aug 2004	1738.6	1.26E+09
Sep 2004	1687.2	1.22E+09
Oct 2004	1214.0	8.76E+08
Apr 2005	1253.9	9.05E+08

Probability Plot of Cycles 15hp Spare Drive Gear
Lognormal - 90% CI

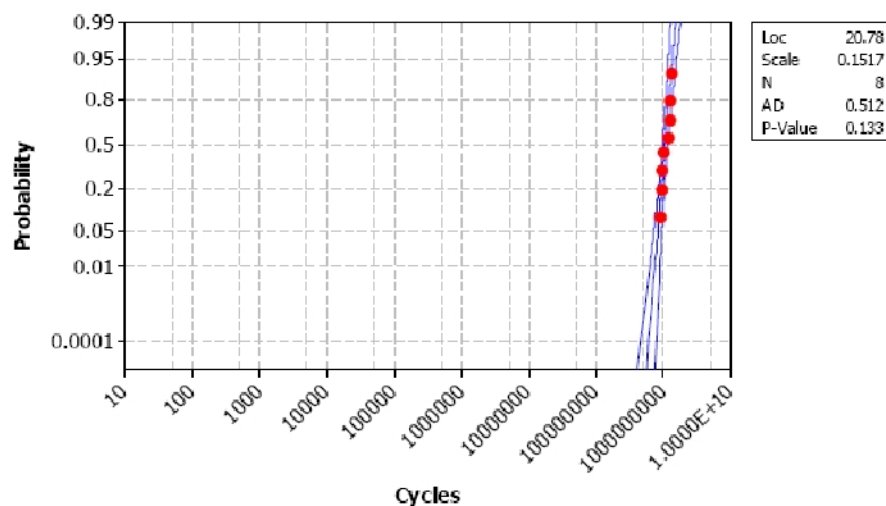


Figure 2. Probability of failure vs. spare drive gear life

Photos of sample post failures of the pinion and spare drive gear are shown in Figures 3 and 4. These photos are typical of all the failures that occurred. A fatigue origin in the root radius area is shown in Figure 5 and the detached teeth collected post failure are shown in Figure 6.

The case hardness, case depth, and core hardness were measured in each of the failed gears. Sample findings are listed in Tables 2. The microstructure, chemistry, and hardness of the spare drive gears and the pinion gears were evaluated and determined to meet all drawing requirements.

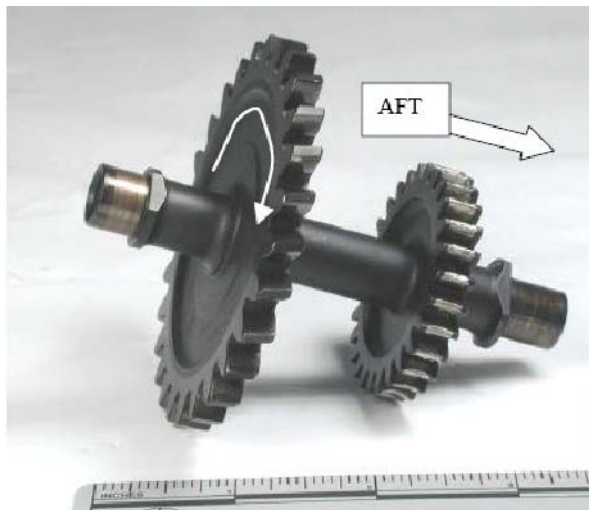


Figure 3. Failed pinion



Figure 4. Failed spare drive gear

Table 2. Sample measurements of spare drive gears

	Pinion	Gear
Case hardness	HR15N 91	HR15N 90
Case depth at root	0.018 in.	0.020 in.
Case depth at 1/2 tooth	0.020 in.	0.022
Core hardness	HRC 40	HRC 40

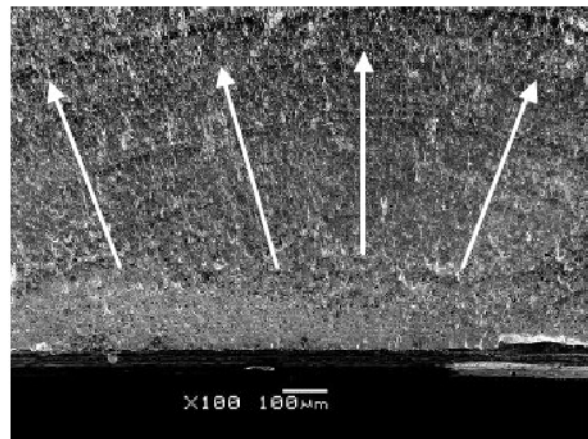
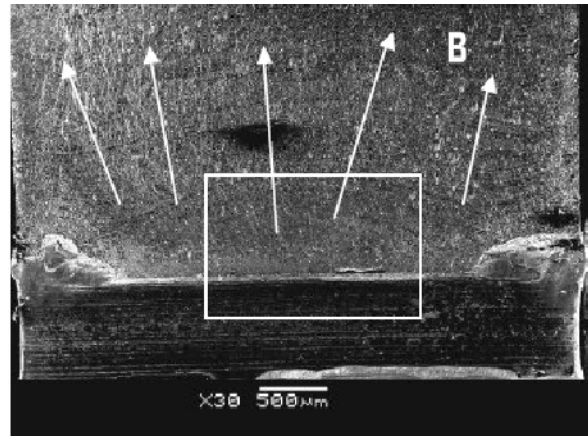


Figure 5. Sample SEM images of fatigue origin area and crack propagation



Figure 6. Condition of detached spare drive gear teeth

A nonfailed spare drive gear and the mating pinion gear were removed by field mechanics and returned for investigation. The gear set had visible wear on the loaded tooth surfaces. The pedigree of this gear set is listed in Table 3.

These two gears were manufactured during the same period as the bending fatigue failures. Further, the gears had accumulated near the same number of cycles as the bending fatigue failures.