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Natural Fatigue Crack Initiation and Detection in High Quality Spur Gears

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There is a desire in the rotorcraft community to transition to an "on condition" maintenance program. This requires the ability to detect the presence of faults before failure. Gear-tooth root-cracks are of particular concern in the drive system, for they are generally difficult to detect until a crack has progressed to the point where catastrophic failure is eminent. Many diagnostics are developed using experimental data generated from specimens with machined, seeded faults rather than naturally developed cracks. The study presented here develops a methodology for seeding natural tooth root-cracks in gears for use in diagnostic experiments. Fatigue cracks are generated on a load frame and then test gears are run on a rotating fatigue rig instrumented with accelerometers. Data presented shows that by comparing baseline healthy vibration data to cracked gear data, damage can be detected with commonly used condition indicators. However, these indicators were not able to show propagation of the crack because the load capability of the contact fatigue rig was insufficient and propagation did not occur.

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ABSTRACT

There is a desire in the rotorcraft community to transition to an "on condition" maintenance program. This requires the ability to detect the presence of faults before failure. Gear-tooth root-cracks are of particular concern in the drive system, for they are generally difficult to detect until a crack has progressed to the point where catastrophic failure is eminent. Many diagnostics are developed using experimental data generated from specimens with machined, seeded faults rather than naturally developed cracks. The study presented here develops a methodology for seeding natural tooth root-cracks in gears for use in diagnostic experiments. Fatigue cracks are generated on a load frame and then test gears are run on a rotating fatigue rig instrumented with accelerometers. Data presented shows that by comparing baseline healthy vibration data to cracked gear data, damage can be detected with commonly used condition indicators. However, these indicators were not able to show propagation of the crack because the load capability of the contact fatigue rig was insufficient and propagation did not occur.

INTRODUCTION

The rotorcraft community is transitioning toward a condition based maintenance (CBM) approach where diagnostic equipment provides real-time component health information on vital drive components such as gears and bearings. Current technology in drive system diagnostics is not reliable in identifying fatigue cracks in drive gears before catastrophic failure occurs. In order to facilitate a CBM program without compromising the safety of the equipment and operators, the diagnostic technology must be able to provide early warning of fatigue failure using sensing equipment readily available to the aviation industry. Historically, research conducted in gear tooth fatigue cracks has been done with artificially created machined notches at the root of the tooth. Combining a single gear-tooth bending-fatigue capability with a high-speed, gear mesh contact-fatigue rig allows for the initiation of naturally occurring fatigue cracks followed by propagation analysis in a rotating mesh apparatus. The objective of this experiment was to initiate a natural fatigue crack and detect its presence before a drive-system-compromising failure occurred by analyzing condition indicators within the vibration signals received by high speed accelerometers.

Gears are designed to fail as a result of wear and pitting on the surface of the tooth before failure of the tooth or rim. This is because tooth and rim failure is often catastrophic and results in damage or destruction of the machine in which it operates. This study is focused specifically on tooth and rim failure.

Significant research has been done regarding crack initiation and propagation; however, until recently this has been artificially induced by machining notches at the base of the tooth [1]. While this method allows for the measurement of crack propagation, it does not accurately simulate fatigue failure in a gear tooth, nor does the resulting vibration signal depict that of a true naturally-grown crack.

Studies have been conducted at both the NASA Glenn Research Center and the Rochester Institute of Technology regarding natural fatigue-crack initiation using a high-cycle gear-tooth bending-fatigue apparatus and measuring the propagation of these cracks while being loaded in a gear-mesh fatigue rig [2,3]. The method used in detection and analysis of the cracks uses condition indicators (CIs) derived from the vibration of the gearbox. These CIs are well documented in literature, and their methods are described in [4-6] including the process of obtaining signal averages and

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the process of filtering such averages. The FM4 and M8A CIs, discussed in this paper, are designed to indicate localized damage on a small number of teeth.

In this experiment, the gears are "broken in" on a gear contact-fatigue rig to obtain the gear-pair's baseline vibration characteristics. The crack is then initiated on a high-cycle single gear-tooth bending rig. The cracked gear is then returned to the rotating contact-fatigue rig, where vibration signals are collected and then analyzed. This method of crack initiation and detection has the potential to provide insight into the shortcomings of the crack detection methods currently used in onboard health and usage monitoring systems (HUMS), as well as the timeframes associated between crack initiation and catastrophic failure of the gear tooth itself.

TEST APPARATUS

The experiments for this paper were conducted using two test rigs at NASA Glenn Research Center. The high-speed Single Gear-Tooth Bending Test Facility was used in order to quickly generate a naturally grown tooth root crack. This facility consists of a 1000 Hz High-Cycle Fatigue Test System produced by the MTS Systems Corporation with a special test head shown in Figure 1. The load arm applies a cyclic load to the test tooth at the highest point of single tooth contact. A reaction tooth, located 2 teeth from the test tooth, counteracts the applied load through the reaction anvil, which contacts the reaction tooth at its root [2]. For ease of discussion, this rig will be referred to as the tooth bending rig for the duration of this paper.

The NASA Glenn Research Center Spur-Gear Fatigue Test Rigs (referred to here as rotating fatigue rigs) have been used for more than 30 years to test new lubricants and loss of oil characteristics, with an emphasis on the study of gear contact-fatigue. These rigs, shown in Figure 2, use the four-square or torque regenerative principle such that the drive motor need only overcome the frictional losses in the system. Torque is applied hydraulically as shown in Figure 2 (b). Oil pressure and leakage replacement flow is supplied to the load vanes within the right side slave gear through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, torque is applied to the shaft. This torque is then transmitted to the test gears. The load on the gear teeth can be changed by altering the flow rate on the pump. The loading system also allows the rig to be started under no load and gradually increase the load while running. Complete specs on this apparatus can be found in [7]. Both the rotating fatigue rigs and the tooth bending rig utilize the same test gears, the design specifications for which are shown in Table 1. The gears utilized in the experiments presented here were manufactured from 9310 gear steel.

PCB accelerometers were mounted on the right side bearing housing between the test and slave gear. While data from 2 accelerometers (one top mounted and one side mounted) was obtained, only data from the top accelerometer is discussed here. Speed was also recorded using an optical tachometer aimed at the rear side of the belt pulley (see Figure 2 (b)) on which a single white line is painted. Data was collected from these sensors in 1 second acquisitions every 60 seconds at 200 kHz for the majority of the tests. Using NASA's Mechanical Diagnostics System Software, data was both recorded and processed after each acquisition, and gear CIs were recorded in a database. Due to the close proximity of the slave gears on this particular rig, the slave gear meshing frequency and harmonics (at multiples of 35 shaft orders including 1st order sidebands) were removed in addition to the test gear meshing frequency, harmonics, and 1st order sidebands. Gear CIs were calculated from the filtered signal average.

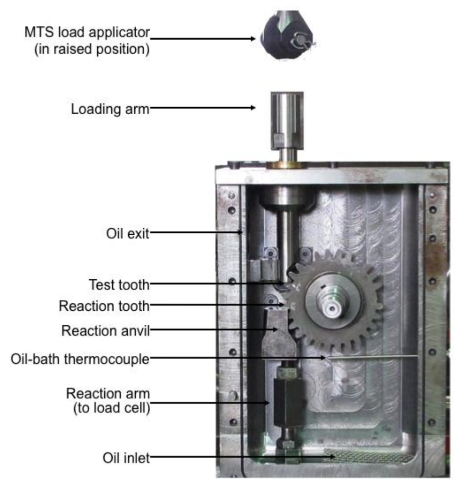
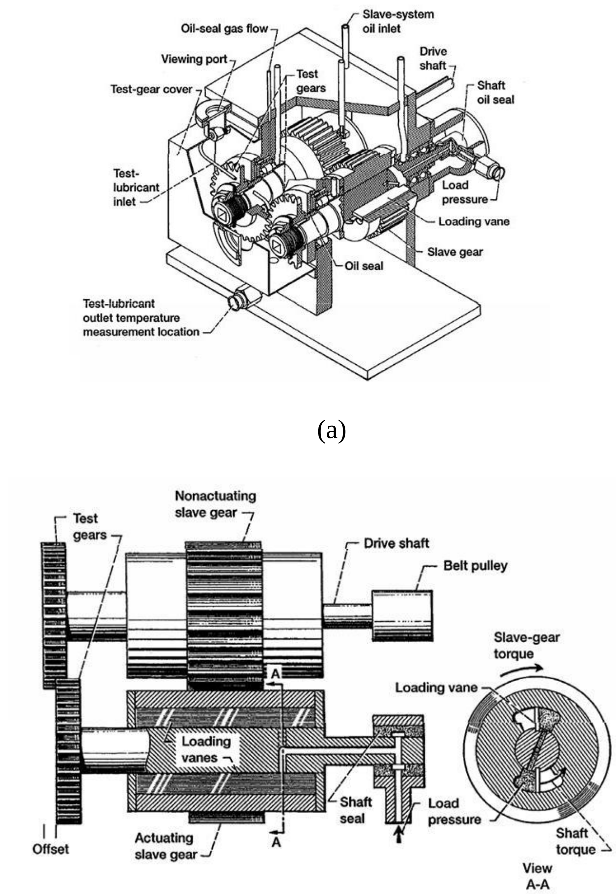


Figure 1. NASA/ARL Signal Gear-Tooth Bending Test Facility [2].

Table 1. Spur gear specimen design parameters [8].

Characteristic	Dimension
Number of Teeth	28
Diametral Pitch (1/in.)	8
Circular pitch (in.)	0.3927
Whole depth (in.)	0.3
Addendum (in.)	0.125
Chordal tooth thickness ref (in.)	0.191
Pressure angle (deg.)	20
Pitch diameter (in.)	3.5
Outside diameter (in.)	3.75
Root fillet (in.)	0.040 - 0.060
Measurement over pins (in.)	3.7867 - 3.7915
Pin diameter (in.)	0.216
Backlash reference (in.)	0.01
Tip relief (in.)	0.010 to 0.015



(a)

(b)

Figure 2. Schematic and cutaway views of the NASA Glenn Research Center gear fatigue test apparatus [8].

METHODOLOGY

Four crack initiation and propagation experiments were performed. The first experiment was used to establish the parameters for crack initiation, the second for method development, and the third and fourth for method validation. Before cracks were initiated, the gears were run on the rotating fatigue rig for up to 2 hours, running until CIs level off from the initial startup transient.

For the first experiment, baseline data was taken at 50 psig load pressure (6.2 ft-lb torque) and 7500 rpm. After the initial break-in period, the gear was placed in the bending fatigue rig and the first tooth was cracked. To crack the tooth, the load applied to the test tooth was cycled between 200 and 3060 lb at 100 Hz. To prevent complete fracture of the tooth, the rig was set to shutdown when the maximum displacement of the tooth increased 2% from the initial maximum displacement. This initial test yielded a large crack measuring 2.4 mm in the tooth. The gear was then placed back into the rotating rig, but tooth fracture occurred before the rotating fatigue rig reached the set speed. The undamaged teeth on this original specimen were then used to determine a better method for initiating cracks on the tooth bending rig (see Figure 3). After several attempts, it was determined that the most reliable way to generate a tooth crack is to set the initial displacement limit at 2%, manually stopping the rig when a crack is visible. If the displacement limit is reached before crack initiation occurs, the displacement limit is increased and cyclic loading is continued until a crack is visible.

During the second experiment, the gear was run on the rotating fatigue rig at 50 psig load pressure (6.2 ft-lb torque) and 7500 rpm for break-in followed by crack initiation on the tooth bending rig. The crack initiation methodology discussed above was used to generate a 2.4 mm root crack. The gear was then returned to the rotating fatigue rig. Several tests were run on the gear at increasing speeds and loads. Little or no propagation of the crack was recorded.

For the third series, it was determined that in order to get results in a timely manner the mesh fatigue rig must be run at maximum load. Thus the break-in for this gear was run at 400 psig (58 ft-lb torque) and 10,000 rpm. After the break-in period, the crack was initiated in the same manner as the previous test. The gear was then run in the rotating fatigue rig. This test was run with the gears offset such that the contact area was cut in half. No visible crack propagation was recorded. However, significant pitting was experienced after running for approximately 12 hours.

Similarly, experiment 4 was run at 400 psi (58 ft-lb torque) at 7600 RPM for 2 hours with no offset. A crack was generated with a depth of 1.5 mm. The gear was returned to the rotating fatigue rig and continued to run for over 70 hours with no increase in crack length.

During each of these experiments, the test gear containing the crack was installed on the right side as viewed from the front (see Figure 2 (a)). A new mating (left side) gear was also installed at the beginning of each baseline experiment. It is also important to note that the crack generated in each of these experiments was visible on both sides of the gear.

RESULTS

In experiment 1, the initial crack was too large and resulted in tooth failure during the start-up of the rotating fatigue rig. Figure 3 shows the gear after validating the crack-initiation procedure. While no statistical data could be obtained from this experiment, it did yield the methodology for further crack initiation.

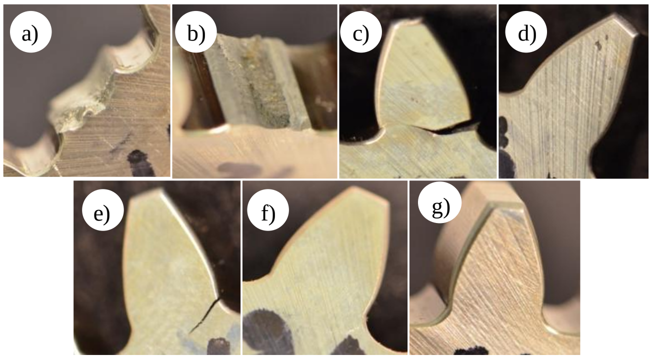


Figure 3. 1st Gear used in the development of a crack initiation methodology. Photos (a-g) represent test teeth 1-7.

The crack generated in experiment 2 is shown in Figure 4. Vibration data, taken during the rotating fatigue rig portion of this test, was processed to obtain the filtered signal averages both before and after crack initiation (Figure 5 (a) and (b)). Filtered signals are created by removing the mesh frequencies and harmonics as well as their first order sidebands from the signal average. The presence of the crack can be seen in Figure 5 (b) at approximately 210 degrees where there is a sudden spike. The frequency spectrum of the signal average before filtering is shown in Figure 5 (c) and (d). The meshing frequency of the test gears can be seen at 28 shaft orders with the first harmonic at 56 shaft orders. Note the increase in the higher order sidebands in the cracked frequency spectrum. These sidebands contribute to the increase in the cracked FM4 CI to 4.5 from a 2.9 baseline and an increase in the M8A CI from 128 to 935.

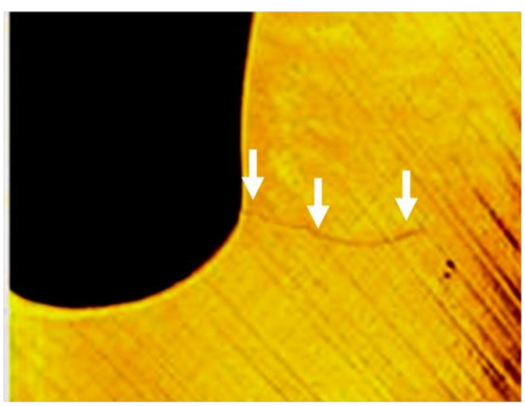


Figure 4. Cracked tooth after experiment 2.

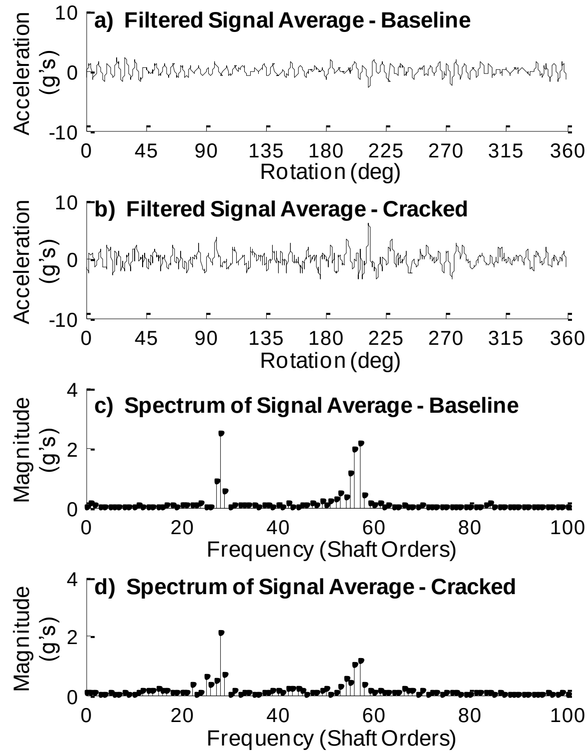


Figure 5. Experiment 2 results at 7500 RPM and 50 psi.

The cracked gear in experiment 2 was run for approximately 14.5 hours at increasing speeds and loads and experienced a crack depth increase of only 0.5 mm. While the crack may have been detectable in the data taken during these higher loads and speeds, baseline data was not recorded at these conditions for comparison. After 8 hours, the gear was also offset, changing the contact area to half the facewidth. Visible surface fatigue damage was generated while running at higher loads toward the end of experiment 2. Pitting on this gear set is shown in Figure 6.

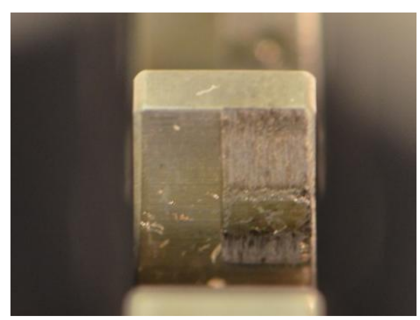


Figure 6. Pitting damage on test gear after experiment 2.

Results from experiment 3 are questionable in that the gears were mounted incorrectly for the first 10 hours on the rotating fatigue rig (including baseline). The gear-pair was mounted such that the bending-fatigue crack was on the opposite side of the tooth, and therefore the load transfer between gears was closing the crack versus continuing to force it open. Upon discovery, the gear was reversed for the last 120 minutes of testing. However, by that time contact fatigue damage was already evident on the "wrong" side of the test gear tooth and had spread to the meshing gear (left side gear). Since the mating gear was not flipped, the test gear was reinstalled in mesh with an already pitted gear, making it nearly impossible to discern between damage due to pitting and damage due to cracking.

Figure 7 shows the filtered signal averages at 4 separate points during testing. Figure 7 (a) and (b) show the baseline data and data taken soon after the gear was installed (incorrectly) after crack initiation respectively. Data taken just before flipping the test gear over is shown in Figure 7 (c), with pitting damage expected between 120 and 270 degrees. The mating gear had already incurred pitting damage at this point and was not flipped. Therefore, the pitting damage on the mating gear is visible in the vibration signal taken shortly after reinstalling the test gear in the correct orientation (Figure 7 (d)). This makes crack identification difficult. A CI comparison between data shown in (a) and (d) shows an obvious increase, but would be an indicator of pitting and not the presence of a crack.

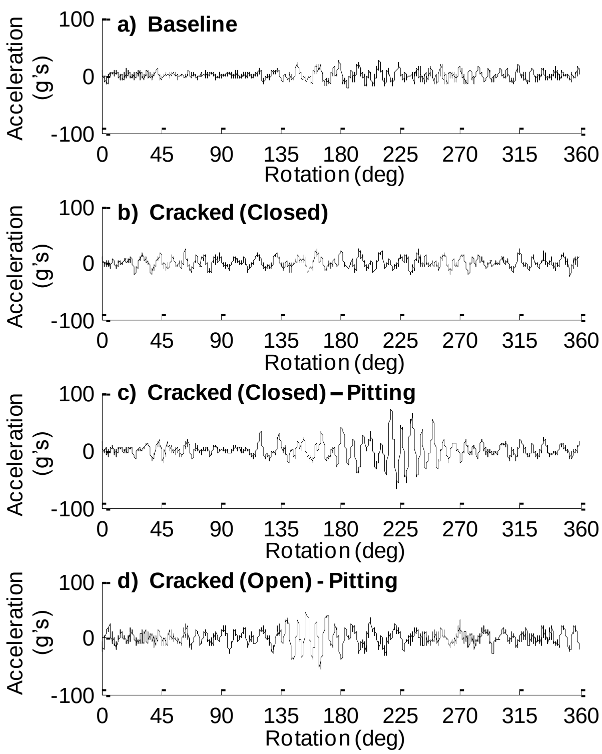


Figure 7. Filtered signal averages for experiment 3 (10,000 RPM, 400 psi) at several points during the experiment with the crack forced open and closed.

Filtered signal averages are shown in Figure 8 (a) and (b) for experiment 4. This experiment utilized a different PCB accelerometer with a higher frequency range (up to 60 kHz). It was installed, as in the previous experiments, on the bearing housing, however, a different housing was used, which could account for the different vibration characteristics. The presence of the crack is visible in Figure 8 (b) in the first 45 degrees of rotation. The frequency spectrum of the averaged signal for both the baseline and cracked cases indicates a dominating vibration at approximately 35 shaft orders. This indicates a strong slave gear meshing vibration. Regardless of this resonance, CIs for this particular experiment show a definite increase: 2.2 to 4.2 for FM4 and 23 to 419 for M8A.

After over 70 hours of runtime 7600 RPM and 400 psi load, there was no visible increase in crack depth. This can be seen in Figure 9, which shows the baseline tooth root along with the initialized crack before installation into the rotating rig and crack after 70 hours of runtime.

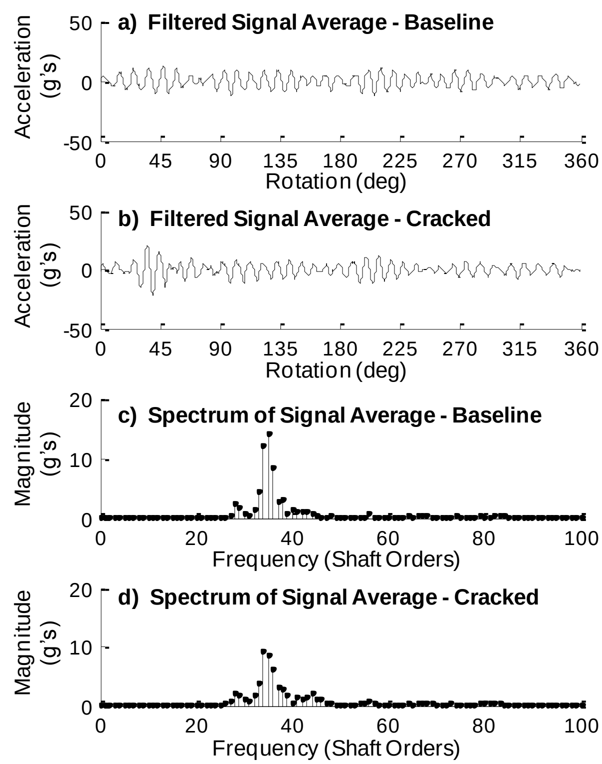


Figure 8. Experiment 4 results at 7600 RPM and 400 psi load.

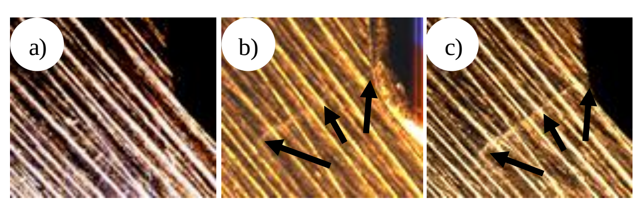


Figure 9. Test tooth root from experiment 4 before testing (a), after crack initiation (b), and after 70 hours of testing (c).

CONCLUSIONS

A methodology for initiating a natural gear-tooth bending fatigue crack using a new high-cycle, single gear-tooth bending fatigue rig is defined, efficiently creating a naturally initiated crack without the removal of material. However, the rotating fatigue apparatus utilized in this study is not ideal for this particular application. The drawbacks of this facility include the close proximity of the slave gears as well as limited loading capabilities. The close proximity of the slave gears in conjunction with the number of gear teeth on the slave gears being similar to that of the test gears complicates fault detection. However, in rotorcraft applications, clean vibration signals are not typical and in this application, the CIs were still able to identify the damage.

Additionally, the loading capabilities of this facility are not sufficient to propagate a crack in a reasonable amount of time. New experimental facilities are available for future tests that both increase the loading capability and separate the slave and test sections. Running comparable experiments on such equipment will allow engineers to gain insight into the vibration characteristics associated with natural tooth root cracks and the timeframe between crack initiation and detection and catastrophic failure of the gear tooth.

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